Final Report

The Tierni Resistance Training System

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Statement of Disclaimer

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I. Executive Summary

The purpose of the Tierni Resistance Training System project was to design and construct functional workout apparel that has built-in resistance. For this product, the key customer requirements we set out to address were most importantly material comfort and functionality, followed by stylishness, lack of latex, safety for injured and uninjured users, and washer safety. To meet these customer requirements, we started by researching current resistance training technology, and used the findings as a springboard for our own design development. After initial brainstorming, engineering specifications were generated based on the customer requirements. These specifications revolved around the thermal insulation, pressure, tensile strength, aesthetic appeal, and melting temperature of the product and its components. The next phase of the design process involved drafting morphology sketches of the prototype, and ultimately narrowing down to a final morphology through concept evaluation. After a final design was agreed upon, a more detailed geometry was created by combining a SolidWorks drawing of the garment components with a lifesize physical mannequin onto which we could place and adjust our garments. Once the design was finalized, we moved forward with manufacturing, which was done primarily using a sewing machine to attach the patches and panels to a set of base garments.

After construction, testing was conducted on the final prototype to see how well it performed against the engineering metrics. Efficacy testing displayed that the resistance garments increased heart rate during lunges and pushups to a statistically significant degree. Furthermore, participant survey results ranked the garments as a 3.67/5 for style, a 4.5/5 for breathability, and a 4.17/5 for overall comfort, all falling within our target values. The results for the pressure testing were inconclusive due to testing equipment issues, however our comfort requirement was addressed in the participant survey. Finally, after reconsideration of our initial specifications for thermal insulation, it was determined that our garments met the breathability requirement. Based on the test results, we are confident that our prototype has the potential to advance further in the design process and ultimately become a marketable product.

II. Introduction

Resistance training has been proven to enhance fitness and build strength, but resistance bands can be uncomfortable, inconvenient, and occasionally cause allergic reactions. This project is focused on eliminating those issues by creating workout clothing that has resistance bands built into its design. The Tierni Resistance Training System project's goal is to create exercise clothing with built-in resistance that is both functional and sleek. To achieve this, we aim to design and construct a prototype for a workout shirt and pants. The stakeholders of any intellectual property generated by this project include our sponsor, Brenae Perkins, and her company.

In the following sections of this critical design report, one can find a more detailed background of our project, as well as a clear list of our customer requirements, objectives, and project management plans. Additionally, we have included the customer requirements and engineering specifications, as well as the details on prototype modeling, manufacturing, and testing. The report is followed by a works cited page and appendices containing supplemental information.

III. Background

In recent years, innovation in the exercise space has reached an all-time high – this innovation has extended into clothing and equipment that enhance physical activity. Despite this advancement, working out is still a mentally-taxing experience for many people. Many products fail to address the mental challenges associated with exercise. For example, resistance bands are a great way to build strength, improve physical fitness, and rehabilitate muscles and joints. However, the current resistance band design is awkward and adds to the physical and mental difficulties that athletes face when working out. Some of these concerns, voiced by our sponsor Ms. Perkins, include the following: resistance bands frequently ride up and require adjusting in the middle of a workout; they may contain latex (a common allergen); they do not interact well with sweat; and they require frequent replacement as they will break down after a few months of use. Several companies have attempted to address this gap, however the current solutions on the market are unattractive and leave some of the customer concerns listed above unaddressed. Exercising can be just as difficult mentally as it is physically. With that, one of the goals of our project is to create a resistance training experience that takes less of a mental toll on athletes.

Accomplishment of our goal to design a clothing article with the appropriate amount of built-in resistance that is still stylish and comfortable will depend on consideration into many key properties of selected materials and fabric construction. The first such property would be the amount of resistance that our chosen fabrics provide against movement or elongation, mostly known as the Elastic Modulus, E. The Elastic Modulus of many individual fiber types are well documented and measured; however, when incorporated into a fabric, the properties of the specific weave used can cause the macroscopic properties of the fabric change with respect to the modulus of individual fibers. The Elastic Modulus of the fabric can be estimated by taking the product of the modulus of its fibers and the volume fraction of the fibers in the fabric as described by Robert W. Williams [1]. Željko Penava, Diana Šimić Penava, and Željko Knezić also showed that the equations for determining moduli in varying directions for anisotropic materials hold with high accuracy for fabrics [2]. Therefore, we believe that accurate theoretical estimates of the product resistance can be calculated and modelled before prototype development.

The comfort level of clothing is also important to consider, and two primary factors contributing to this quality are thermal insulation and cloth pressure. According to Sun Yu, the insulative properties of clothes are primarily dependent on the porosity of the fabric: clothes use individual pockets of air to slow the release of heat from the body while shielding the skin from wind currents that speed up natural heat convection [3]. Choosing a fabric weave of an appropriate porosity will allow us to tailor the heat release of the product such that customers will become overly hot or sweaty upon engaging in activity while using the product. It is also important to tailor the design such that excess pressure is not applied to the body of a customer. M.J. Denton reported that pressures between 20-40 g/cm^2 can result in discomfort to individuals [4]. Additionally, clothing pressure can result in potential damage to the body, such as chafing, rashes, or even pressure ulcers. According to Surajit Bhattacharya and R. K. Mishra, pressure, shear, and friction are 3 of the 6 major causes for pressure ulcers, a breakdown of skin and underlying tissue caused by prolonged or repeated force to the skin surface [5]. Therefore, identifying key areas of pressure on the body and modulating the force applied by the product in those areas will be critical to maintaining client comfort and health.

A. Intellectual Property Assessment

There are several products currently on the market, in addition to traditional resistance bands, that attempt to achieve the same resistance training effects. A summary of these products can be found in Table 1 below. Furthermore, many of these ideas have been patented, and a summary of related patents can be found in Table 2.

Table 1. Related Designs

Existing Designs	Summary of Design Qualities
AGOGIE Wearable Resistance [6]	Pants with built in resistance bands, creating an “exoskeleton of resistance”. Pants have stirrups to anchor bands, are loose fit and are sold with two levels of resistance.
“Stretch” Bands	10”-12” diameter loops with various resistance levels. Allow for use around knees or ankles. Often made from latex.
“Tube” Resistance Bands	Sets of “tube” resistance bands of various resistances accompanied by handles and ankle straps. Allow for stationary use and different levels of resistance during use.
BodyBoss2.0 System [7]	Stationary platform and resistance band system that allows users to exercise with resistance bands in various types of motion. Uses “tube” straps and handles and offers adjustability through implementation of different anchors and handles.
High Compression Workout Clothing	Offers compression during any exercise for a user through skin tight and stretchable fabric that adapts to the user's body.

Table 2. Related Patents

Patent Title	Inventor/Company
Sports Performance Enhancement Systems [8]	Functionwear LLC
Exercise System Using Exercise Resistance Cables [9]	John Bowser
Resistance Band [10]	Thomas Paul Pouliot
Exercise Garment with Ergonomic and Modifiable Resistance Bands [11]	Franklin Yao
Variable Resistance Exercise Band [12]	Alfred Sidney Smith, Jr.

B. Regulatory Codes & Classifications

While exercise equipment requires significantly less regulation than other medical device categories, there are still a handful of industry standards that our product must comply with. These standards and classifications are as follows:

- Clothing Flammability Standards, found in: Code of Federal Regulations in Title 16, Part 1610. All clothing worn in the United States made of textiles must comply with flammability standards. We will not encounter issues complying to regulatory standards as nylon is a fiber that always meets Class 1 regulatory standards, regardless of weight or thread size. [13]
- United States Patent Office Classification: Class 482 - Exercise Devices
  "This class provides for apparatus intended to be operated by a human user for the purpose of: (a) facilitating the conditioning or developing of a muscle of the user by repetitive or continuous activity of the user or, (b) participating in a track, field, gymnastic, or athletic activity, unless by analogy of structure or by other function the apparatus is classified elsewhere." [14]

Per the US Food & Drug Administration; "FDA regulates exercise equipment only if the equipment is intended to be used for medical purposes, such as to redevelop muscles or restore motion to joints or for use as an adjunct treatment for obesity. FDA does not regulate exercise equipment intended only for general physical conditioning and/or for the development of athletic abilities in individuals who lack physical impairment." [15] As such, our product will not necessitate FDA approval.

IV. Objectives and Customer Requirements

Through the Tierni Resistance Training System, we are attempting to address the problem of discomfort and awkwardness experienced by many when using resistance training exercise equipment. The objectives for this project, set for us by our sponsor Ms. Perkins, include the following:

- Perform extensive materials research to determine the best material candidates for the resistance workout apparel
- Gain an understanding of current resistance equipment, taking note of and building off patented technology
- Design a model for a workout shirt that provides resistance to the users upper body muscles
- Design a model for a workout pant that provides resistance to the users lower body muscles
- Construct a functioning prototype made of the ideal materials
- Obtain initial customer reviews and suggestions for product improvement

Because we are limited by resources and a relatively short timeline, there are some goals that lie outside of the scope of this project, but will need to be addressed in the future. These goals include:

- Construction of multiple models of our prototype for different sexes/sizes
- Cultivation of a marketable aesthetic/brand for the workout clothing
- Connection with investors or athletes willing to test out the equipment

Our customers, along with our sponsor Ms. Perkins, want a wearable resistance training system that is both functional and stylish. Furthermore, the apparel should be comfortable, latex-free, safe for injured and uninjured individuals, and be washer and dryer safe. The full list of customer requirements can be found in Appendix A-1.

V. Indications for Use

As a first step in the development of our product, it was important to specify the indications for use. The following explicitly states how we intend our product to be used:

“This product is intended to be worn during low to medium impact exercise to provide resistance to the users’ muscles with the intention of building strength and improving fitness. It is intended for use by individuals weighing more than 100lbs and of at least 13 years of age. If users are recovering from injury in a physical therapy setting, they should have physician approval prior to use. Otherwise, users should be physically healthy and have no injuries that could be worsened by resistance training.”

VI. Project Management

A. Network Diagram

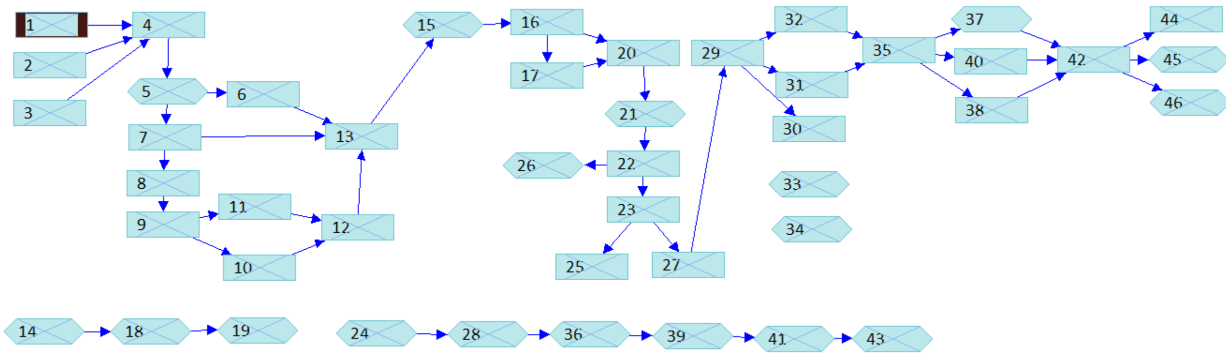

***Figure 1*. Network Diagram.** All tasks on the network diagram were completed, as such the critical path is no longer highlighted, task descriptions can be found in Appendix G.

B. Budget

Table 4. Actual Spending

Item Description	Vendor	Product Number	Purpose	Cost
Lycra/Spandex Sample	Payless Fabrics	LY400	Material Testing	$9.69
100% Nylon Sample	Carr Textile	T-BLK-60	Material Testing	$11.00
80% Nylon, 20% Spandex Swatch	Rex Fabrics	N/A	Material Testing	$16.15
30N Spring Gauge (x3)	Educational Innovations	SP-50	Material Testing	$25.73
Neoprene	Jo-Ann Stores Inc.	400175186309	Prototype Construction	$31.98
Singer Stitching Needles	Jo-Ann Stores Inc.	075691047214	Prototype Construction	$4.19
Nylon Thread	Jo-Ann Stores Inc.	073650776793	Prototype Construction	$7.98
Resistance Bands	Te-Rich	B08MVSSVTV	Prototype Construction	$43.08
Buckles (2” - Plastic)	Aootech	B06XK6Z26V	Prototype Construction	$5.08
Dowels (3” - Wood)	ACE Hardware	52152	Prototype Construction	$2.12
			TOTAL	$157.00

VII. Specification Development

After the customer requirements were set in stone, a house of quality analysis was performed to convert the customer wants into measurable engineering specifications. Furthermore, the house of quality helped determine which of the specifications were of the most importance and would therefore require the most energy and time to develop. Table 5 lists some of these important engineering specifications, and the complete house of quality can be found in Appendix A.

Table 5. Engineering Specifications

Requirement	**Parameter Description**	**Requirement/Target**	**Tolerance**	**Risk**	**Compliance**
Comfort	Thermal Insulation	0.03 Clo*	±0.01 Clo	M	S
Comfort, Safe for Injured and Uninjured	Pressure	15g/cm^2	Max	M	T, S
Functional (Provides Resistance)	Tension	5 lb	±2.5 lb	M	T, A
Stylish	Aesthetic Appeal	65% approval on 5 point scale	Min	L	I, T
Dryer Safe	Melting Temperature	135 F	Min	L	S, I, A

* The Clo is a unit of thermal insulation equivalent to 0.88 ft2·°F·h/Btu. [16]

Because the current plan of design is to augment standard industry design with unique functional materials, many of the specifications can be verified through similarity to current products. Whether or not the product breathes enough for clients to feel comfortable and whether the product will be dryer safe can both be verified by similarity to predecessors. In this case, similarity will be evaluated by the construction and material composition for the device. If the bulk of the product is constructed from an industry-standard material (such as nylon) with a common weave type, then it will possess a similar ability to insulate heat or fit the body. We can additionally know that the bulk of the product will be dryer safe, and we can then focus on testing the unique functional components for dryer safety. Finally, we can verify these conclusions by product comparison tests. The functional tension of the material will be verified with a standard fabric tensile test in order to plot the stress-strain curve and calculate the modulus of elasticity as well as the force applied to clients. We plan to examine the aesthetic appeal of the product via customer survey ratings. Finally, applied pressure can be evaluated by taking readings from pressure sensors worn by a model using the product. Detailed plans for testing each product specification are discussed in the Test Protocol section of this report.

We believe that there are no high-risk specifications. The first reason for this is that there are no majorly conflicting customer requirements. This removes the difficulty of balancing two priorities that impede each other as well as the process of finding a constructive solution to satisfy both. Secondly, the product possesses a lot of functional and design similarity to previous items. This allows us to adapt designs that have already satisfied many of the requirements, and thus we can focus our efforts and analysis on the unique functional elements of the product.

A. Conjoint Analysis

Once we had accumulated our customer requirements, we conducted a conjoint analysis survey and computed an ANOVA on the results to determine which of the requirements is the most important to the customer. The three factors we tested in the conjoint analysis were color scheme, degree of waterproofness, and dryer compatibility. Out of these three factors, the factor that had the largest correlation with customer approval, and therefore will have the most impact on the success of our product, is the dryer compatibility.

Specifically, we found that the dryer compatibility category had a p-value of 8.25E-6 with a regression coefficient of 1.047619. The p-value shows that the correlation in customer ratings was significant, and the positive correlation shows that higher customer rankings- where higher ranking was recorded as a lower score, indicating that a favored product was ranked as #1 for example- correlated to dryer friendly products. The statistical analysis output can be found in Appendix A.

VIII. Morphology Sketches

After determining our engineering specifications and evaluating properties that were critical to customer satisfaction, we created a morphology of possible product construction and features in Appendix C and generated several product concepts.

Our first concept sketch consists of normal athletic wear with selective panels of specialty material sewn. The panels adopt designs similar to back and knee braces in order to provide support and remain comfortable. The cloth is two-toned, with a stirrup at the foot of the leg as well as thumb and finger holes at the feet and hands to prevent wrinkling and maintain aesthetic appeal.

For our second concept sketch, magnets can be placed into the tight, fitted pockets that have an opening at one end in order to provide resistance to the users' muscles. Additionally, mesh paneling is placed strategically throughout both the shirt and pants to provide for breathability and comfort. The entire garment, for both the shirt and pants, is one uniform color and has straight-across seams at both the ankles and wrists, as opposed to the stirrup design, for stylistic appeal.

Our third and final concept sketch has elastic fibers that are woven into specific regions of the garments to provide resistance in targeted muscle groups. The garments are constructed with sweat-wicking nylon base fabric that provides a "hugged" feeling for the user. The garments are uniform colored (black) and have seaming at the collar, cuffs and bottom of each garment, as opposed to stirrups or thumbholes.

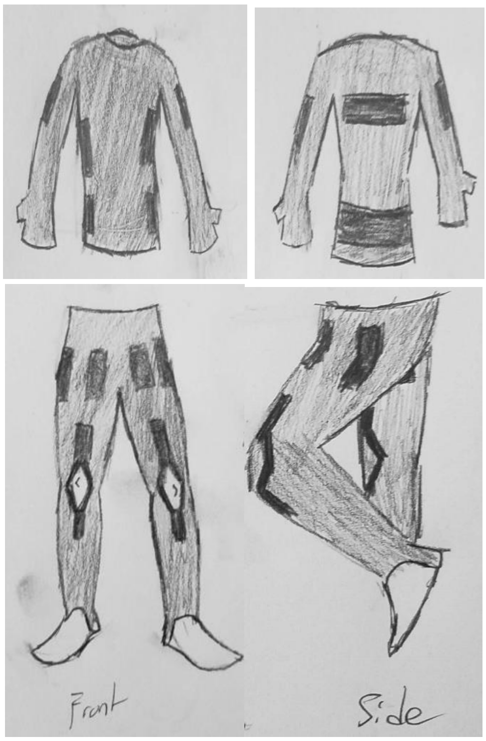

Figure 2. **Concept Sketch 1.** Design consists of paneling, brace design, stirrups/thumbholes, and a two-toned color scheme.

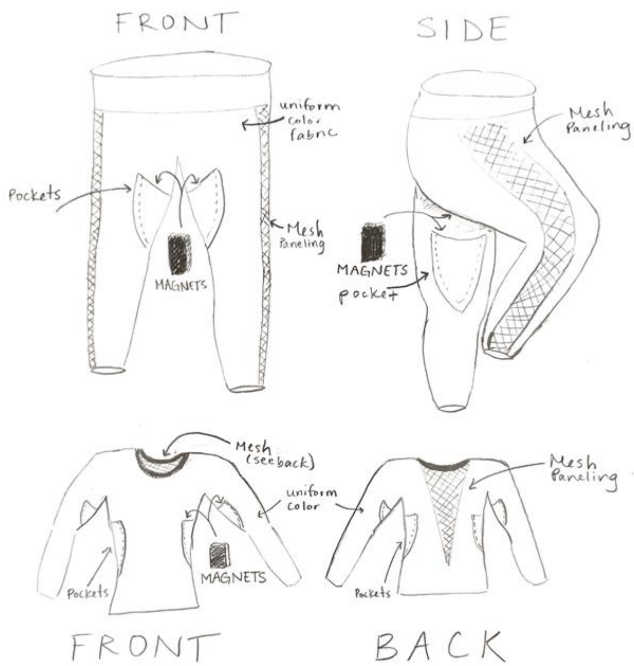

Figure 3. **Concept Sketch 2**. This concept sketch utilizes magnets, mesh, no stirrup or thumbholes, and has a uniform color scheme.

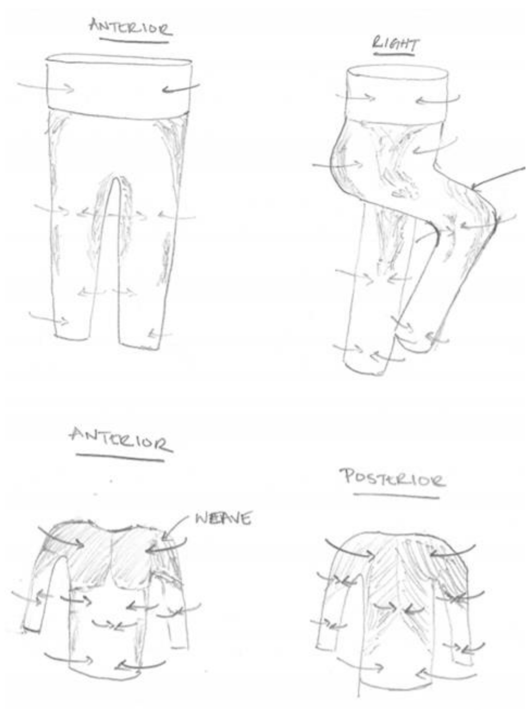

Figure 4. **Concept Sketch 3.** This concept sketch has specific weaved regions of the elastic material, a hugged feel for, no stirrups or thumbholes, and a uniform color scheme.

Following return from our academic break in December, our sponsor requested an amendment to our original design. The request made was that visible resistance providing elements would be added to the garments. Our original morphology sketches did not include visible resistance band elements. In order to address the requests of our sponsor, we developed new sketches that would meet the new customer requirements. See sketch below.

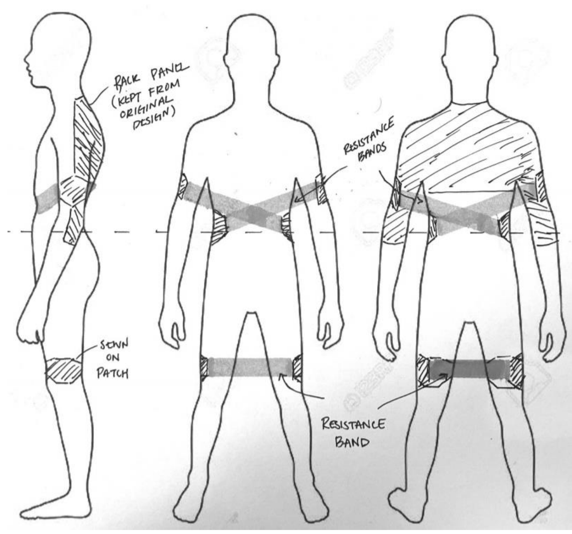

Figure 5. **Concept Sketch 4.** This concept sketch has patches through which resistance bands will be fed and a large resistant panel across the shoulder blades.

Our sponsor approved of the design changes, including the removal of the panel from the bottom garment and the addition of two resistance bands incorporated into the design of the top garment to match the requested changes to the design of the bottom garment, so our team proceeded with further development of the concept and refined the design.

IX. Concept Evaluation

Once we had developed our three frontrunner concept sketches, the next step was to compare and evaluate each of our designs. We did this comparison using Pugh charts, with our requirements being ease of use/practicality, dispersion of pressure, stylistic appeal, and breathability. We assigned weights to each of these requirements, and then evaluated each of these designs using a different concept as the baseline for a total of three Pugh charts per group member. We had each group member separately fill out their own Pugh charts so that we could get a larger diversity of opinions, especially considering some of our requirements (such as stylistic appeal) are more subjective. Table 6 is an example of one of the Pugh charts produced from this analysis, and the rest of the Pugh charts can be found in Appendix B.

Table 6. Sample Pugh Chart - Concept 1 as Baseline

Requirement	Weight	Baseline	Concept 1: Paneling	Concept 2: Magnets	Concept 3: Weaved Regions
Ease of use/Practicality	30	Datum	1	-1	1
Dispersion of Pressure	35		0	-1	1
Stylistic appeal	20		-1	1	1
Breathability	15		0	1	0
	Total		0	0	3
	Weighted Total		10	-30	85

Based on our Pugh chart analysis, there was one clear front runner that scored the highest on all of our scales. This front runner was Concept 3, which uses specific weaved regions of the leggings to provide resistance. While the paneling concept was a close second based on its high scores in ease of use, the weave concept ultimately prevailed as it also had high scores in stylishness and dispersion of pressure. The magnet concept's best feature was its breathability, but we can easily incorporate the mesh areas from the magnet model into the weaved regions model.

After this concept evaluation, our sponsor directed us to include visible resistance bands attached to the clothing instead of trying to integrate them into it. This resulted in making modifications to our selected concept. While we still included material panelling in some areas (mainly the back) to provide resistance, the rest of the paneling was primarily used as a means to anchor and attach standard resistance bands.

X. Conceptual Model

From our Pugh chart analysis, a "weave in specific region" model was chosen as the appropriate design to develop a conceptual model for. Given the lack of information and due to feasibility constraints, our team opted to perform a conceptual model more closely related to the "panel design". The "panel" and "weave" designs were meshed to reflect a conceptual design of panels being placed into specific regions of the garments.

The goal of our model was to determine materials that would meet design specifications for desired fatigue properties of the resistance providing material in our garments. We first determined design specifications of the resistance providing material that would be integrated into the base garment fabric. The following procedure was designed to aid in material selection (under the assumption that the specialty material would provide 5 lbf of constant resistance to user:

Conceptual Model Procedural Design:

1. Calculate area of each band of specialty material.
2. Divide 5lbf by that area to calculate a desired stress.
3. Evaluate the highly elastic region of each elastomer to determine a material that has an elastic region at that stress.
4. Record what strains the desired stress occurs at.
5. Determine how much the material will stretch during use.
6. Use the stretch length and initial strain to determine the length of material incorporated and how long it should be stretched for static conditions.

We performed steps 1 and 2 of the procedure and found that our desired stresses are 371 and 159 kPa for the panels of fabric we are designing. Cross sectional areas of 1 mm x 6 cm and 1 mm x 14 cm were used respectively in order to determine stress. 5 lbf was converted to Newtons in order to perform calculations in SI units. We used preliminary sketches to determine the desired width of the panels of resistant fabric, and a detailed sketch of fabric panel location on the body is shown in Figure 6.

Upon determining target stress for our specialty material, we determined the amount of cycles our product would be designed to withstand. We assumed the product would be worn by a user twice per week and would withstand 8,000 daily cycles, we assumed the average user would walk 8,000 steps in the product during each use. We are designing the product to withstand 2 years of use and determined the product would need to withstand 1.7 million cycles before fatiguing. We also determined the product would need to withstand 11 hours of static stress for each usage assuming that the user would wear the product for 11 hours during each use. Hand calculations are shown in Appendix D.

We then compared our design specifications to stress-strain curves of possible materials and determined that none of the materials would act as perfect elastomers under the stresses our product will be under, but found that Spandex would act most closely to meet design specifications and needs. Following comparing design specifications to stress-strain graph elastic regions, we looked to S-N graphs to determine if potential materials would fatigue before the desired 1.7 million cycles. We determined none of the materials would fatigue under product design specifications and assumptions. S-N curves for Nylon and Rubber are shown in Appendix D as well.

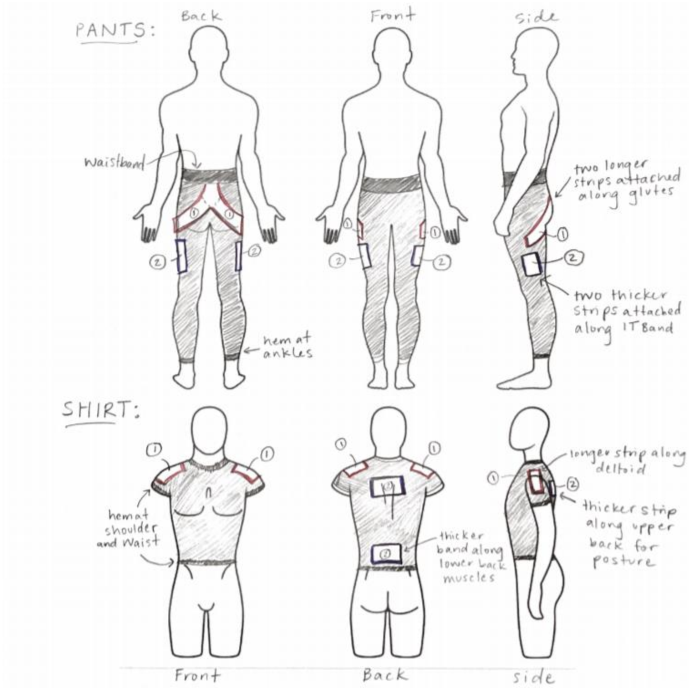

Figure 6. **Conceptual Design Sketch.** Sketch is a more detailed model that incorporates the set areas 1 and 2 of resistant material that were used in the engineering calculations.

After our initial concept sketches, our sponsor voiced that she wanted to be able to visually see the resistance band go across the legs and arms. With that in mind, we designed the sketch seen in Figure 5. In this sketch, patches of material are attached to the base garments. The patches are attached on the top and bottom seams, but left open on either side so that a resistance band can be fed through the patches and effectively held in place. Additionally, there is one large resistant panel attached to the top across the shoulder blades.

In development of our new design, we needed to determine the height at which to attach pathwork to allow the easy attachment of the resistive elements. Using a life size mannequin form, our team experimented with different patch dimensions and attachment sites on the garments that would be used for our functional prototype. Figure 8 shows the final locations and patch sizes we attained through testing.

This practice also led to an amendment in the design of our back panel. Given the finalized location of the patchwork on the upper body, we were able to streamline our design of the patchwork and remove superfluous material from the design we developed in morphology sketches. All finalized dimensioning and location points are diagrammed and discussed in the following section.

Figure 7. **Patchwork Conceptual Model.** Patchwork was designed and tested at various attachment locations. Finalized patch dimensions and placement are reflected in the image.

XI. Detailed Design

The final design for our product consists of a combination of paneling and patches through which the resistance bands are fed. The final material will be attached to prefabricated garments that will fit skin tight for the user. The final paneling design is an iteration of previous design concepts and models. With maximizing primary function for the user and risk assessment in mind, larger panelling will be used in our final design plans.

To establish an appropriate geometry and dimensioning for the resistant material, a physical mannequin form was used to create physical templates for the panelling. Dimensioning and geometry is based on a “Small Female” mannequin form and can be scaled to fit larger or smaller users. The patches were strategically placed such that the tensions applied when the resistance bands are fed through will not cause pinching or other discomfort. Additionally, the panel was designed to wrap around the shoulders to pull the shoulder blades back with the intent of improving the wearer’s posture. The geometry on a mannequin form is shown in Figure 8. The finalized dimensions of the patches and panels that will be used for prototyping are shown in Figure 9. To incorporate user-adjustability, we designed a resistance band mechanism with buckles that easily allow for tightening and loosening. This mechanism was not included in the assembly drawing in Figure 8 for simplicity’s sake, however it can be observed in Figure 10 of the final prototype. Former iterations of this design can be found in Appendix H. The final design is estimated to cost $62-67 dollars for a full set (top and bottom garment).

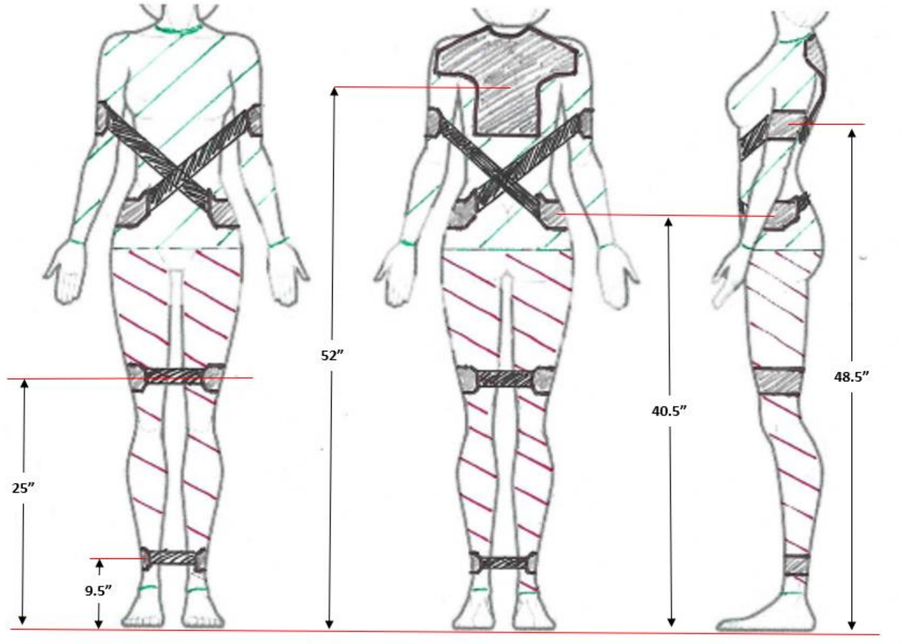

Figure 8. **Assembly Drawing with Panel Distances from Ground.** Distance, as measured from ground to center of each patch, is shown for all patches and panelling for both top and bottom garments. Dimensions are given in inches.

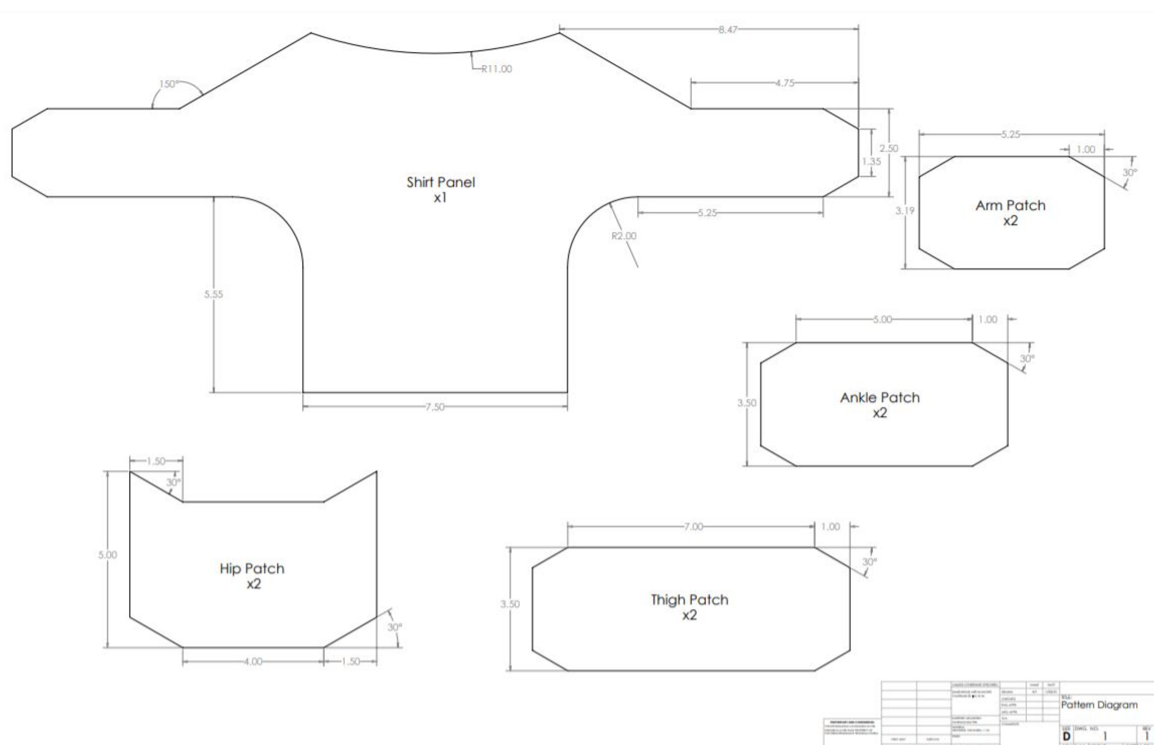

Figure 9. **Solidworks Drawing of Neoprene Patches and Panel.** All critical dimensions for patchwork are shown on the above image. All dimensions are in inches and degrees and each piece has a thickness of 0.1 in.

XII. Final Prototype

Figure 10 displays the fully constructed final prototype. As seen in the figure, there is a top and bottom garment with resistance bands incorporated into the design. The following section of this report describes how this prototype was constructed.

Figure 10. **Final Prototype.** Consists of the completed resistant pant and shirt with incorporated buckle-band mechanism. Garments are displayed on a size 6 (per manufacturer sizing scale) female mannequin.

XIII. Prototype Manufacturing Instructions

Once we defined our geometry and measurements, the next step was to determine how to construct our prototype. For the initial prototype, we purchased prefabricated athletic tops and bottoms, and attached the patches and panel of neoprene in the regions defined by our detailed geometry (the patches are the regions through which the resistance band will be threaded, while the panel is the large area of neoprene located on the back of the top). The first step was to cut out the patches/panels of neoprene according to the dimensions necessitated by our geometry. Then, the patches were pinned to the base garments in their respective locations so that they would stay in the correct place during sewing.

To attach the panels, we used a Brother LS-2125i Sewing Machine, a picture of which can be seen in Figure 11. Although this sewing machine does not have the same capabilities as the serger machines used in industrial manufacturing of athletic wear, it was able to manage the neoprene and base garment material reasonably well and sufficed for our prototyping needs. We sewed the large panel onto the base top along all of its edges. The patches were attached on only the top and bottom edges, leaving the sides open so that a resistance band could be fed through. The stitch we used to attach the resistant panels to the base garments is called the Straight Stitch [22]. This stitch is supported by the Brother LS-2125i sewing machine, does not cause any waves or wrinkles in the fabric to form, and is aesthetically attractive. We used a jersey needle because they are less sharp than universal sewing needles, which can pierce the knit threads and cause holes to form in the fabric. Furthermore, we used a black all-purpose polyester thread, as it is the most versatile and more flexible than standard cotton thread.

***Figure 11*. Brother LS-2125i Sewing Machine [22].**

For the construction of the buckle-resistance band mechanism, prefabricated resistance bands were purchased, along with male and female ends of plastic buckles. The resistance bands came as a continuous loop, which we cut and melted the ends of to prevent fraying. These ends were then fed into both the male and female ends of the buckle. The male end of the buckle was intended to be permanently locked in place, while the female end was adjustable. To lock the male end in place, we looped the resistance band through the buckle and fed a wooden dowel through the loop to prevent any movement of the band.

Table 7 below is our bill of materials, which lists each item necessary for manufacturing. The specific Manufacturing Process Instructions can be found in Appendix F. It is important to note that future mass production of our product will certainly take on a different manufacturing process. That being said, for preliminary prototyping, this simplified manufacturing process allowed us to create a fully functional and testable product.
Table 7. Bill of Materials

Item #	Part #	Qty	Name	Material	Source
1	47199	1	Wunder Under High-Rise Tight 25" (Base Pant)	69% Nylon, 31% Lycra® elastane	Lululemon Athletica
2	45852	1	Swiftly Tech Long Sleeve 2.0 (Base Top)	54% Nylon, 40% Recycled polyester, 3% Elastane, 3% X-static® nylon	Lululemon Athletica
3	17518630	2 yds	WUJI MDGRY Solid Neoprene	Polyester face/back and neoprene middle	Joanne's Fabrics
4	60100	2	All-Purpose Polyester Thread	Polyester	Amazon, Singer
5	2583938	1	Schmetz Ball Point Machine Needle (5 pack)	Nickel-plated high carbon steel wire	Joanne's, Schmetz
6	B08MVS SVTV	2	Resistance Bands (3 pack)	Cotton and Rubber	Amazon, Te-Rich
7	B06XK6 Z26V	1	2 in. Plastic Buckles (12 pack)	Plastic	Amazon, Aootech
8	52152	3	3 in. Wooden Dowels	Wood (White Oak)	Ace Hardware

XIV. Instructions for Use

Many of the customer requirements for our product revolve around user-friendliness. That being said, it was important that our instructions for use be comprehensive and easy to follow. Listed below are all the steps necessary to take when using the Tierni Resistance Training System, from putting the clothes on to the proper washing technique.

1. Feed resistance bands through desired patches

a. One end of the buckle will be permanently attached to the resistance band. Completely remove the other end of the buckle from the resistance band.
b. Feed the buckle-free end of the bands through the desired patches.
c. For the upper body patches, feed the band through the upper arm patch and then through the patch on the opposite hip. The bands should cross to form an X shape.
d. Depending on which muscle groups the user wants to exercise, the resistance bands can be fed through the according patches (thigh, ankle, or arms).

2. Put on garments as you would any normal athletic wear.
3. Tighten resistance bands using buckle attachment to desired tightness. The tighter the band, the harder the workout will be.
4. Safely perform your medium to low impact workout.
5. To remove, first unbuckle the bands, and then take off garments. Once the garments are off, it is easier to completely remove the buckles and resistance bands from the garments.
6. Machine wash the garments in cold water and lay flat to dry out. Do not put the garments in the dryer. Make sure to completely remove the resistance bands before washing.

After construction of our initial prototype, testing was performed to determine if our product met the design specifications. The next section explains how we conducted these critical tests.

XV. Testing Protocol

Two categories of testing were performed to evaluate whether the prototype met the engineering specifications. The first round of testing was performed prior to the construction of the prototype, and served as initial material testing (specifically tensile testing) that was conducted at home using a modified procedure. The second round of testing was carried out on the completed prototype. These tests include general efficacy testing, as well as testing for the thermal insulation, pressure, aesthetic appeal, tensile strength, and melting temperature of the prototype components. The specific procedures for these tests are described in the following sections.

A. Initial material testing

Due to limitations in equipment availability as a result of COVID, material testing occurred in two phases. The first phase was performed at-home using a modified tensile testing procedure. In order to do this, a force gauge was purchased and secured to a door handle using the metal loop at the top of the gauge. Material samples were then attached to the gauge using binder clips with sand paper to improve grip strength of the clips. The material was cut into a rectangle of known width and was clamped into the binder clip to attach it to the force gauge. Next, a ruler was secured to the side of the door from which the material sample and force gauge have been hung. Then, the material sample was pulled down until measurable increments of force have been achieved. Pictures from a mounted camera were taken at each level of force, and the images were analyzed with ImageJ software to calculate how much the material strained at each applied force. Images of the experiment setup and plots of the stress-strain behavior of several preliminary materials can be examined in Appendix E.

This at home tensile testing procedure was performed first on a sample of rubber acquired from a traditional resistance band. We used these results as the baseline to which we compared our experimental materials. The experimental materials included nylon, spandex, a nylon-spandex blend, and later neoprene. Neoprene behaved the most similarly to rubber, and we therefore decided to move forward with neoprene as the main resistant material for our product. Although we ended up changing directions from using neoprene as the physical resistant material to simply using it as a patch to hold a resistance band in place, the information gained from this study was still helpful for the development of the back panel on the shirt. The stress strain curves that were calculated from these tests for all of the materials can be found in Appendix E.

The second phase of initial material testing was performed once we obtained access to campus testing facilities, particularly the INSTRON tensile testing machine. At this point in the design process, we were still considering using neoprene as the resistance band material. We used this INSTRON test to determine if this would be possible. The results of this tensile test showed that neoprene did not behave closely enough to rubber, and could therefore not be used as our main resistant material. However, we were able to conclude from this study that neoprene could withstand the typical tensile forces exerted on athletic clothing when it is stretched. With that in mind, we made the decision to use neoprene as the patches to hold the resistance bands in place rather than serving as the resistance bands itself. The stress-strain curves obtained from this test can also be found in Appendix E.

The following tests were conducted on the entire finished prototype. These tests include the efficacy of the prototype, as well as tests for the pressure, thermal conduction, aesthetic appeal, resistance, and washer safety testing, which are described in more detail in the following subsections.

B. Efficacy Testing

The first set of experiments performed were to evaluate product efficacy. To do this, we used the following procedure, performed by Abby and Michael from 2/26/2021 to 3/6/2021:

<u>Safety Precautions</u>:

- All participants and team members will be required to wear single-use surgical masks provided by the senior project group.
- All participants and team members will maintain at least six feet of physical distance at all times, per CDC guidance.
- A maximum of three team members and two participants will be onsite at a given time.
    - Participant start times will be offset by 15 minutes such that only one participant is going through intake/instructions with a team member at a time.

    - Only one team member will manage each participant, while a second team member will be managing the second participant, and the third team member will be performing data processing and equipment handling and cleaning duties.
- All participants and team members will be required to use provided hand sanitizer prior to handling any equipment or clothing materials.
- Senior project team members will wear gloves when handling all equipment.
- Wrist-worn heart rate monitors will be sanitized following each use.
- All garments will be sanitized and washed prior to another study participant wearing the garments.
- Participants will change clothing in a provided outdoor tent, which will be sanitized before and after each use.
- Participants will be required to show a negative COVID-19 test result and will be instructed not to participate in the study if they have any symptoms of COVID-19.
- A questionnaire (either the Cal Poly Screener or one that team members will provide if the participant is not on campus) will be filled out on the day of testing, prior to arriving onsite, to confirm that no symptoms are present.
- Participants will undergo a temperature check upon arrival to verify that they are not showing a fever.
- Participants will be asked to come alone to the testing site.

This experiment required the following:

- 2 Heart rate monitors
- 12 Participants
- 2 Examiners

<u>Procedure:</u>

1. After a temperature check, the participant will begin the protocol in the designated outfit. Half of participants will start in standard activewear, and the other half will start with the product.
2. The participant will put on a wrist-worn heart rate monitor and read out their resting heart rate for a team member to record.
3. The participant will perform a 2-minute walk with 100 steps per minute as the standard walking pace.
4. The participant will then resume their resting position for a team member to record their heart rate.
5. The participant will rest for 5 minutes to return their heart rate to a resting condition. Then, the team member will record their heart rate again to obtain a resting heart rate for the next test.
6. Steps 2 through 5 will be repeated, but instead of performing a brisk walk, the participant will perform 1 minute of push ups.
7. Steps 2 through 5 will be repeated, but instead of performing a brisk walk, the participant will perform 1 minute of lateral raises.
8. Steps 2 through 5 will be repeated, but instead of performing a brisk walk, the participant will perform 1 minute of lunges.

9. After completing step 8, the participant will switch which garment they are wearing, either from standard activewear to the product or from the product to standard activewear depending on which they started in.
10. Steps 2 through 8 will be repeated.

Product efficacy was determined by examining a significantly different increase in the heart rate of participants when using the product. Each participant's heart rate was measured using a heart monitor. To collect statistically relevant data, we evaluated our data using a paired t-test with a 0.05 level of significance, 80% power, and 0.8 effect size. This required a sample size of at least 12 participants. The experiment null hypothesis is that the mean heart rates post-exercise will be equivalent, with a 1 tailed alternative hypothesis that post-exercise heart rate will be increased for participants using the product. We expect that the product will have a statistically significant effect.

C. Thermal Conduction Testing

The third experiment conducted was used to determine if we met our product specification for thermal conduction. The following procedure was used in formal experimentation by Gabriel on 3/4/2021 at Cal Poly, room 192-328:

<u>Safety Precautions:</u>

- Both examiner and overseeing technician will wear facial covering and maintain 6 foot separation as per CDC guidance.
- Only 1 team member and 1 lab technician will be present.
- Both the team member and technician will have a negative COVID 19 test and display cal poly self screening examination to show that no COVID symptoms are present.
- All equipment will be disinfected after use.

These procedures will require the following:

- 1 Hotplate
- 6 Ice cubes
- 1 Prototype model
- 1 Scale
- 1 Stop watch

<u>Procedure:</u>

1. Heat a hotplate to 65 C.
2. Place paper towels on scale and zero the measurement.
3. Measure and estimate the area of the icecube.
4. Weigh icecube to determine mass.
5. Track how much water was left on the paper towels during measurement.
6. Place product material on the hot plate, and place the ice cube on top.

7. Use a stopwatch to keep exact time.
8. Wait for at least 10 minutes.
9. Weigh the remainder of the cube to determine how much ice has melted.
10. Repeat steps 1-9 for a total of 5 tests, one on each of the following areas: the nylon of the leg, the nylon of the waistband, the neoprene patch of the ankle, the nylon of the shirt's stomach, and the nylon of the armpit.
11. Repeat steps 2-9, this time placing the icecube on a set of paper towels that are not on the hotplate. This is used as a control to calculate the heat transfer rate caused by the room over the time period.

We calculated the coefficients of each area in the prototype. Then, we compared these values to our target value and tolerance. Additionally, we quantized user experiences by taking a second comfort survey in the same format as the first.

D. Pressure Testing

The second experiment is used to determine if we met our product specification for clothing pressure. The following procedure was used in formal experimentation by Gabriel on 3/4/2021 at Cal Poly, Room 38-133:

Safety Precautions:

- Both examiner and overseeing technician will wear facial covering and maintain 6 foot separation as per CDC guidance.
- Only 1 team member and 1 lab technician will be present.
- Both the team member and technician will have a negative COVID 19 test and display cal poly self screening examination to show that no COVID symptoms are present.
- All equipment will be disinfected after use.

In order to conduct this experiment, the following resources were required:

- 1 Powerlab pulse transducer
- 1 Mannequin
- 1 Prototype model

Procedure:

1. Examiner fits product onto mannequin
2. Examiner places the pressure sensor within the clothes in several spots while recording the pressure readings from the cloth.

We compared the pressure readings to our maximum threshold value of 15g/cm^2, noting any extreme values and where they occur. We also quantized participant experiences by taking a survey of the participants of the first experiment set. Participants were asked to rate their overall comfort wearing the product on a 1 to 5 scale, 1 being low comfort and 5 being high comfort. The participants were also asked to separately rate the least comfortable area of the product. We averaged these ratings to see if they met a target value of at least 4 for overall comfort, and at least 3 for the least comfortable area.

E. Aesthetic Appeal Testing

The fourth set of experiments was used to verify the aesthetic appeal of the product. We asked participants to rate the style of the product on a scale of 1 to 5, with 5 being high style and 1 being low style. We then averaged these ratings and compared them to our minimum threshold of 3.25.

F. Resistance and Washer Safety Testing

Because we are now providing resistance through use of common resistance bands, we will determine the product resistance by inspection of the weight specification on the bands we have purchased instead of testing them. Additionally, we will no longer be testing for dryer safety due to changes in the design made during our sponsor guidance in meetings.

XVI. Testing Data and Analyses

A. Efficacy Testing

During product efficacy testing, two one tailed, paired t-tests were performed. The first test compared the elevated heart rates of participants without using the product against the elevated heart rates of participants while using the product. For the second test, we calculated the difference between the elevated and resting heart rates of the participants to create two sets of differences: one for when the participants were not using the product and one where the participants were using the product. These sets of differences were compared to see if the product successfully elevated the heart rate effectively. The p-values were examined to determine which exercises the product made a significant difference in. While the full collection of data and calculation is available in Appendix J, a graphical representation of heart rate means is shown in Figure 12 and the corresponding p-values are shown in Table 8.

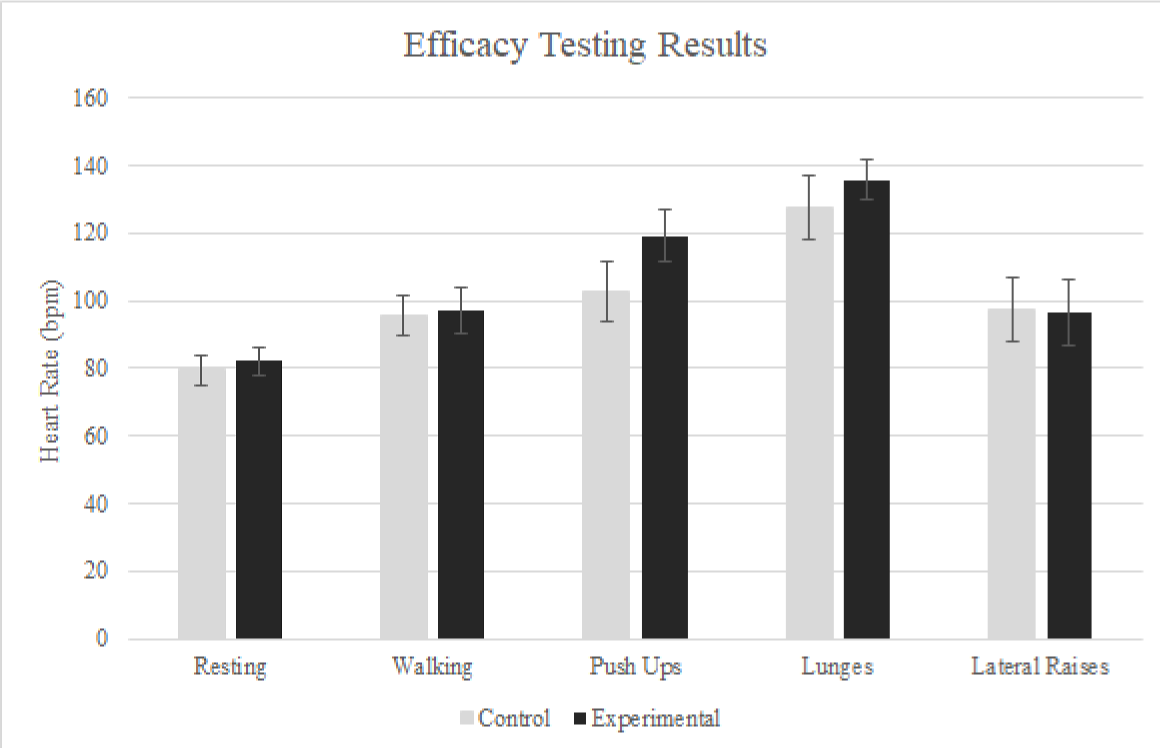

***Figure 12*. Average participant heart rates under control and experimental conditions.** Error bars are standard errors of difference in mean. Averages for push ups and lunges are statistically different with $p < 0.05$ (using alpha = 0.05).

Table 8. P-values for comparison of heart rates

	Overall Heart Rate p-value	**Heart Rate Elevation p-value**
Walking	0.3999	0.4265
Pushups	0.006100*	0.008439*
Lunges	0.04839*	0.07623
Lateral Raises	0.3558	0.01115*

*indicates statistical significance with $p < 0.05$

B. Thermal Insulation Testing

During thermal insulation testing, we recorded the mass of ice prior to heating, in addition to the amount of water that was left behind after the initial weighing. These two values were subtracted in order to determine the total mass of ice present at the beginning of the heating process. We then recorded the mass of ice remaining after the heating process, in addition to the amount of time the ice was being heated. The final mass was subtracted from the initial mass to determine the mass of ice that melted during this period. This quantity was then multiplied by the heat of fusion of ice and divided by the amount of time spent melting to determine the total rate of heat transfer to the ice during testing. A control was measured by performing the same procedure while allowing an ice cube to melt on an unheated surface. These measurements were used to calculate the heat transfer rate to the ice cubes by the room, and this value was subtracted from the previously calculated heat transfer rates to determine the exact rate of transfer through the material. The temperature differential from the hotplate to each ice cube was multiplied by the cross-sectional area of each cube and divided by these heat transfer rates to determine the total Insulation Constants of each area of the prototype. While the full set of recorded data and calculations is located in Appendix J, the final calculated values are in Table 9 below.

Table 9. Thermal Insulation Constants

Tested Area	**Insulation Constant (Clo)**
Leg	0.1673
Waistband	0.3862
Ankle Patch	-58.32
Stomach	0.1696
Armpit	0.3200

C. Pressure Testing

During the pressure testing, a powerlab pulse transducer was placed under the clothing in seven areas: the hip, the buttock, the middle of the back of the calf, the middle of the outside of the calf, the shoulder blade, the edge of the deltoid, and the waist. Two measurements were taken for each spot: one on the right side and one on the left. These values were averaged for a final value in each area. Measurements were taken after a minute in order to allow stress-relaxation to occur. A control measurement with an object of known weight was taken to convert the powerlab readings of volts to pressure. While the full data collected is available in Appendix J, the final results are shown in Table 10.

Table 10. Garment pressure on the body

Body Part	Average Pressure (g/cm^2)
Hip	0.6562
Buttock	0.5937
Back Calf	0.4625
Mid Calf	0.4078
Shoulder Blade	0.4375
Deltoid	0.2969
Waist	0.2844

D. Customer Surveys

The results from the post-testing questionnaire were averaged to obtain the final answers shown below in Table 11. The complete questionnaire with questions and responses can be found in Appendix I.

Table 11. Survey Averages

Style	Breathability	Overall comfort (pressure)	Least-comfortable area (pressure)
3.67	4.5	4.17	2.83

XVII. Discussion

The objective of the design process for the Tierni Resistance Training System was to produce a fully functional top and bottom garment that incorporated resistance into the design. Furthermore, the product was intended to provide the user a less mentally taxing workout while maintaining a “sleek” and “bold” design, as requested by our sponsor, Ms. Perkins. The design process began in the establishment of engineering specifications, forming a house of quality and followed with material selection, the preliminary research and subsequent material testing. Our design process included several stages of iteration, including a pivotal change in overall design structure necessitated due to feedback from our customer. These steps were followed by prototype construction and evaluation.

Our experimental results for product efficacy concluded that the product provided a statistically significant increase in heart rate for high-intensity exercises such as push ups and lunges, but not for low-intensity exercises such as walking and lateral raises. Running the same statistical analysis on the values of heart rate elevation showed a statistically significant change in heart rate in only pushups and lateral raises. However, we believe that the significant difference in lateral raises is an outlier, as further investigation revealed that the mean heart rate elevation decreased while participants performed lateral raises under experimental conditions. There are several sources of error that may have impacted the results. The first source is the use of two separate heart rate monitors, that may have differing accuracy and precision levels. What is known is that both of them only displayed heart rate after a significant delay, meaning that any reading taken was not the instantaneous value. Additionally, due to restraints related COVID-19, the sample size for this study was relatively small, which resulted in underpowered study results. Therefore, the validity of our statistical analysis is uncertain.

Our experimental results concluded that our specifications for thermal insulation were not met. While our thermal insulation specification required us to meet a value of 0.02 clo, our calculated thermal insulation values ranged from 0.167 to 0.386 clo, with an extreme outlier of -58 clo. Several sources of error contributed to these results. The first of these was experimental constraints. Our experiment relied on measuring the mass of single ice cubes as they melted at a low temperature differential. This increased measuring error with lost fluid and increased effect of room-temperature environmental heating. A more accurate experimental setup would have involved measuring the mass of water in an ice bath over a larger temperature differential (100-200C) in order to determine the mass of ice that had melted. However, this setup was unviable for two reasons. Our product relies on a somewhat sensitive fabric, therefore we could not increase the heat gradient without damaging the prototype. Additionally, we did not have the supplies to prepare several ice baths, and without a large heat gradient, increased masses may have obscured the small amount of mass melted. A second error is that the cross-sectional area over which heat transfer took place is an estimate, as the sloped nature of the ice cubes caused the area to change over the melting period. In regards to the extreme value of -58 clo, we believe that it would be justified to ignore this value. The value was calculated from one of the areas of the body including neoprene. What this tells us is that the value of the heat transfer rate through the neoprene possesses an order of magnitude so small that it is obscured by any error and heat transfer caused by the room environment.

Despite not meeting our specification for thermal insulation, we believe that our results are acceptable and that the project can continue forward. When the development team set our product specification for thermal insulation, we used the ASHRAE thermal insulation value for pantyhose equalling 0.02 Clo. Our logic for this was that tights are the same garment as pantyhose by definition: the only difference between the two is that traditional athletic tights have larger thickness and fiber linear density. However, this comparison between the two ignores that fact that insulation increases with density and thickness. After obtaining our experimental results and checking that no calculation errors occurred, we reconsulted the ASHRAE handbook. The team discovered that our calculated thermal insulation values actually lie within a range set by several other potentially more appropriate clothing analogs. Thin trousers hold an insulation of 0.15 Clo, while sweatpants have an insulation of 0.28 Clo. In regards to shirts, thin, long sleeve dress shirts sit at 0.25 Clo while sweatshirts have a value of 0.34 Clo. In regards to our extreme value from the neoprene patch, our team had expected neoprene to interfere with breathability but concluded that the neoprene patches constitute a small enough surface area that their effects can be ignored. Future participant testing could be used to evaluate this hypothesis. Our customer survey for breathability met the set specification, so we believe that our failure to heat our thermal insulation specification was a result of missetting the specification instead of design failure. Therefore, we believe that the project can continue forward.

We do not believe any meaningful conclusion can be drawn from our pressure test data. This assertion stems from experimental error due to severe equipment limitations. The pulse transducer pressure sensor appears to only evaluate relative measurement. While attempting to take a control measurement to convert the pulse transducer data to pressure, the experimenter and lab technician noticed that the pulse transducer readings started at 1 mV, while the original experimental data had crossed below the 1mV threshold. The steady state value of the control measurement showed a pressure increase that exceeded any value displayed in experimental data, even assuming that the experimental data had a base reading of 0 mV. Additionally, constant voltage decay was observed. The resulting calculations concluded that at no point did the pressure of the garments exceed the amount of pressure that would be applied by resting a penny on one's leg. Our efficacy testing participant reviews of garment pressure tell us that this conclusion is false. In regards to the pressure comfort surveys, the participant reviews for overall comfort met our specifications. However, the reviews for the least-comfortable area in particular did not. We are unsure if a conclusion can be drawn from either of these surveys, as we were only able to collect reviews from 7 participants due to COVID restrictions, and several participants wore garments that were undersized for them.

The survey results from our Aesthetic appeal testing met our specifications. Our dryer safe specification to test the melting point of the product was not examined, as we did not have the budget to damage production materials as part of such a test. However, due to the presence of neoprene in the prototype, and to the base garments not being dryer-compatible, the design team has concluded that the prototype is not dryer safe. Despite not being dryer safe, we were able to successfully wash and air dry the garments multiple times. While this differs from our design specification, we still believe that we can move forward with the design, as our sponsor-requested redesign led us to eliminate dryer safety as a specification for the current design.

XVIII. Conclusion

Based on the results from the prototype testing, the Tierni Resistance Training System serves as a functional resistance garment that is comfortable, stylish, and washer safe. Our data gathered supports the conclusion that the garments are functional in providing a workout. For both lunges and pushups, lower and upper body workouts respectively, statistical analysis yielded a p value of less than 0.05, thus there is evidence to support that the garments enhance a workout (as defined by increasing heart rate). Qualitative analysis of the product also suggests the product met customer specifications for comfort and style. Users ranked the garments higher than our threshold approval rating of 65% for aesthetic appeal and 80% on 5 point scale. In thermal insulation testing, we were able to conclude that the garments meet criteria for analogous products that would be worn during exercise, despite not meeting our original engineering specification, which we now believe to have been a misguided specification. Our pressure testing did not yield viable data, but we believe the product meets requirements through user survey validation. Given the limitations to our study due to COVID restrictions and equipment malfunction, we suggest that larger studies be completed to further validate the findings that the Tierni Resistance Training System provides functionality for the upper and lower body for a user.

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APPENDIX

Appendix A: Project Goals & Product Specifications

A. 1. List of customer requirements, in order of most to least importance according to sponsor:

1. Comfort
2. Functional
3. Stylish
4. Safe for injured & uninjured
5. Various models (male/female)
6. Washing/Drying safe
7. Latex free

A. 2. Conjoint Analysis ANOVA

Factors and Levels for Conjoint Analysis

Factor	**Level 1**	**Level 2**
Color Scheme	Uniform Color	Two-toned
Degree of Waterproof	Sweat Proof	Entirely Waterproof
Dryer Friendly	Yes	No

Conjoint Cards

- 111: Uniform Color, Sweat Proof, Dryer Friendly
- 122: Uniform Color, Entirely Waterproof, Not Dryer Friendly
- 212: Two-toned, Sweat Proof, Not Dryer Friendly
- 221: Two-toned, Entirely Waterproof, Dryer Friendly

Conjoint Analysis ANOVA Excel Summary Output

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.476666
R Square	0.227211
Adjusted R	0.198231
Standard E	1.007118
Observatic	84

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regressior	3	23.85714	7.952381	7.840376	0.000118904
Residual	80	81.14286	1.014286		
Total	83	105			

	Coefficients	*andard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*pper 95.0%*
Intercept	0.571429	0.58146	0.982749	0.328694	-0.585712861	1.72857	-0.58571	1.72857
Color Sche	0.190476	0.219771	0.866703	0.388697	-0.246882161	0.627835	-0.24688	0.627835
Waterproc	0.047619	0.219771	0.216676	0.829013	-0.389739304	0.484977	-0.38974	0.484977
Dryer Frier	1.047619	0.219771	4.766865	8.25E-06	0.610260696	1.484977	0.610261	1.484977

A. 3. House of Quality

The Tierni Resistance Training Program

WHO | Engineering Requriements (HOW) | Competition (NOW)

Customer Requirements (WHAT) 8 = most important; 1 = least important		Brenae (Sponsor)	High score on 5-point attractiveness scale by >65% of users	Product contains no latex in areas that may come in contact with human skin	Primary material provides sufficient resistance when strained 20%	Primary material provides compressive force when not strained	Material porosity is such that it will allow for sweat and water vapor to easily pass through	Material has sufficient ultimate tensile strength such that bands do not break when exerted to 640 lbf of force	Material has sufficient yield strength such that the bands return to their original length after being stretched with a force of 320 lbf	Product provides sufficient resistance training to cause muscle fiber damage & rebuilding, specifically to the triceps, quads, and glutes	Material is permeable to fluids when completely submerged in water	Material melting temperature is above 135 °F	Material maintins mechanical properties for over N = 200,000 cycles (4 years)	Material is resistant to creep when repeatedly exposed to 135 °F
			↑ points	↓ %	↑ lbs	↑ Pa	↑ %	↑ MPa	↑ Mpa	↑ %	↑ kPa*s/m	↑ °F	↓ # cycles	↑ # cycles
	Provides Resistance	7			•	•		•	•				•	
Functional	Safe for injured & uninjured	5			o	•		o	o	Δ				
	Training for football & basketball players	3			o					•			Δ	
	Sweat wicking	4					•							
Comfortable	Latex Free	1		•										
	Compressive	8				•		o	o					
Washer & Dryer Safe		2					o				•	•		•
Stylish		6	•				Δ							
	Importance		7.36	1.22	11.85	24.52	6.54	13.9	13.9	4.36	2.45	2.45	8.99	2.45
	AGOGIE		3	0	10	2	20	16	16	80	0.06	100	150,000	100
	Traditional Resistance Bands		2	50	15	2	0	15	15	80	0	300	100,000	300
	Target		4	0	18	3	50	16	16	90	0.08	300	200,000	300
	Threshold		3	10	12	2	20	15	15	80	0.05	135	150,000	135

Competition (NOW): 1 2 3 4 5

* AGOGIE

\# Traditional Resistance Bands (Latex + Rubber)

Strong Correlation	• = 9
Meduim Correlation	o = 3
Small Correlation	Δ = 1
No Correlation	Blank

Appendix B. Concept Evaluation Pugh Charts

B. 1. Abby's Pugh Carts:

Concept Sketch 1 as Baseline

Requirement	Weight	Baseline	Concept 1: Paneling	Concept 2: Magnets	Concept 3: Weaved Regions
Ease of use/Practicality	30	Datum	1	-1	1
Dispersion of Pressure	35		0	-1	1
Stylish	20		-1	1	1
Breathability	15		0	1	0
	Total		0	0	3
	Weighted Total		10	-30	85

Concept Sketch 2 as Baseline

Requirement	Weight	Baseline	Concept 2: Magnets	Concept 3: Weaved Regions	Concept 1: Paneling
Ease of use/Practicality	30	Datum	0	1	1
Dispersion of Pressure	35		0	1	1
Stylish	20		1	1	-1
Breathability	15		1	0	0
	Total		2	3	2
	Weighted Total		35	85	45

Concept Sketch 3 as Baseline

Requirement	Weight	Baseline	Concept 3: Weaved Regions	Concept 1: Paneling	Concept 2: Magnets
Ease of use/Practicality	30	Datum	1	1	-1
Dispersion of Pressure	35		1	0	-1
Stylish	20		1	1	1
Breathability	15		0	0	1
	Total		3	2	0
	Weighted Total		85	50	-30

B. 2. Gabe’s Pugh Charts:

Concept Sketch 1 as Baseline

	Weight	Baseline	Concept 1	Concept 2	Concept 3
Ease of use/Practicality	30	Datum	1	0	1
Dispersion of Pressure	35		1	0	1
Stylish	20		-1	1	1
Breathability	15		0	1	0
	Total		1	2	3
	Weighted Total		45	35	85

Concept Sketch 2 as Baseline

	Weight	Baseline	Concept 2	Concept 1	Concept 3
Ease of use/Practicality	30	Datum	0	1	1
Dispersion of Pressure	35		0	1	1
Stylish	20		1	-1	1
Breathability	15		1	0	0
	Total		2	1	3
	Weighted Total		35	45	85

Concept Sketch 3 as Baseline

	Weight	Baseline	Concept 3	Concept 2	Concept 1
Ease of use/Practicality	30	Datum	1	0	1
Dispersion of Pressure	35		1	0	1
Stylish	20		1	1	-1
Breathability	15		0	1	0
	Total		3	2	1
	Weighted Total		85	35	45

B. 3. Michael’s Pugh Charts:

Concept Sketch 1 as Baseline

Requirement	Weight	Baseline	Concept 1: Paneling	Concept 2: Magnets	Concept 3: Weaved Regions
Ease of use/Practicality	30	Datum	1	-1	0
Dispersion of Pressure	35		1	-1	1
Stylish	20		0	0	1
Breathability	15		0	1	1
	Total		2	-1	3
	Weighted Total		65	-50	70

Concept Sketch 2 as Baseline

Requirement	Weight	Baseline	Concept 2: Magnets	Concept 3: Weaved Regions	Concept 1: Paneling
Ease of use/Practicality	30	Datum	-1	0	1
Dispersion of Pressure	35		-1	1	1
Stylish	20		0	1	0
Breathability	15		1	1	0
	Total		-1	3	2
	Weighted Total		-50	70	65

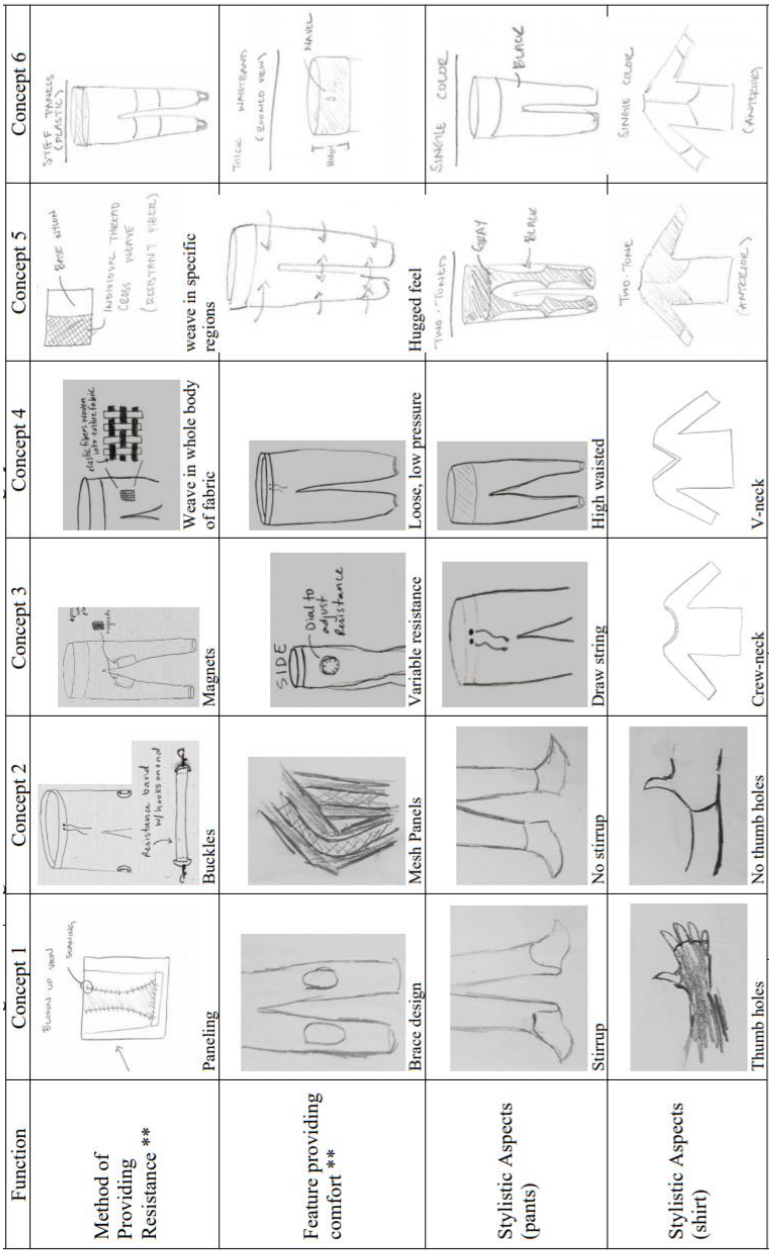
Concept Sketch 3 as Baseline

Requirement	Weight	Baseline	Concept 3: Weaved Regions	Concept 1: Paneling	Concept 2: Magnets
Ease of use/Practicality	30	Datum	0	1	-1
Dispersion of Pressure	35		1	1	-1
Stylish	20		1	0	0
Breathability	15		1	0	1
	Total		3	2	-1
	Weighted Total		70	65	-50

Appendix C. Morphology Sketches

C.1: Morphology Sketches

Function	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6
Method of Providing Resistance **	Paneling	Buckles	Magnets	Weave in whole body of fabric	weave in specific regions	
Feature providing comfort **	Brace design	Mesh Panels	Variable resistance	Loose, low pressure	Hugged feel	
Stylistic Aspects (pants)	Stirrup	No stirrup	Draw string	High waisted		
Stylistic Aspects (shirt)	Thumb holes	No thumb holes	Crew-neck	V-neck		



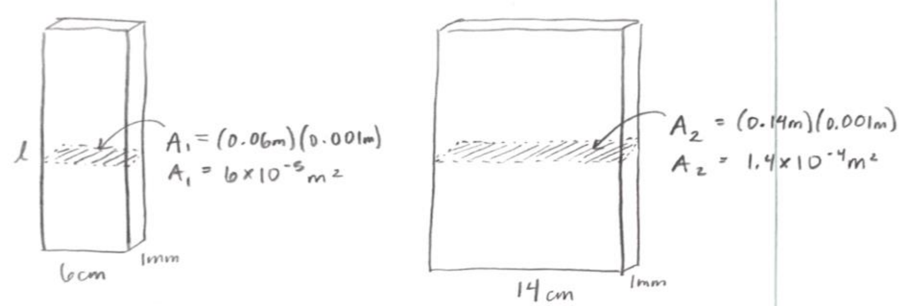
Appendix D. Conceptual Model Details

D. 1. Conceptual Design Hand Calculations

Stress Calculations:

- Two areas, one thinner one thicker
- Approximate 5 lbs of force will be applied to the material in one cycle

Area 1 Area 2



Convert Force $\quad 5lbf \cdot \frac{4.448N}{1\,lbf} = 22.2411\text{ N}$

Calculate stresses

$$\sigma_1 = \frac{F}{A_1} = \frac{22.2411\text{ N}}{6\times10^{-5}m^2} \approx 371\text{ kPa}$$

$$\sigma_2 = \frac{F}{A_2} = \frac{22.2411\text{ N}}{1.4\times10^{-4}m^2} \approx 159\text{ kPa}$$

Daily cycles & Product life:

- Approximating 8,000 steps a day for athletic individuals
- Assume clothing will be worn twice a week
- Want clothing to last at least 2 years

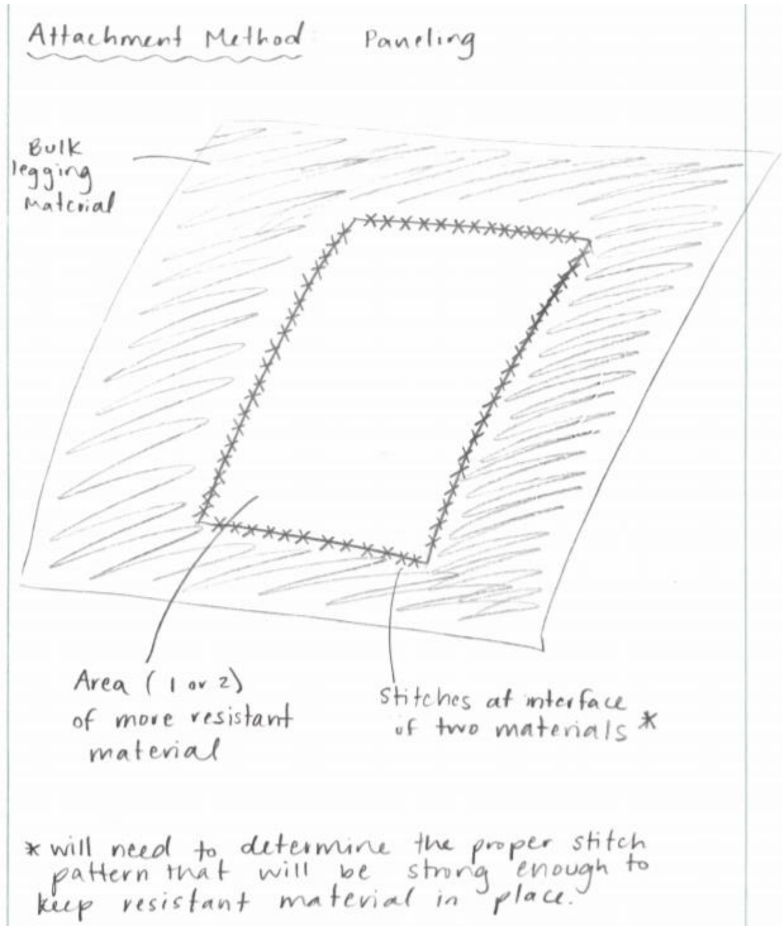
$$\frac{8{,}000\text{ cycles}}{\text{day}} \cdot \frac{2\text{ days}}{\text{Week}} \cdot \frac{52\text{weeks}}{1\text{yr}} \cdot 2\text{yrs} \approx 1.7\text{ million cycles}$$

Static Stress Assumptions:

- Material should maintain mechanical properties when exposed to one day of static stress

$\rightarrow$ 11 hours

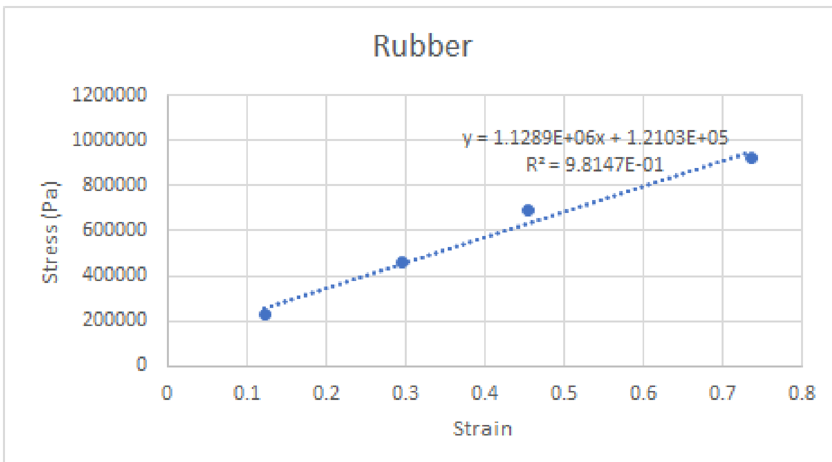
D. 2. Panel Attachment Method Sketch



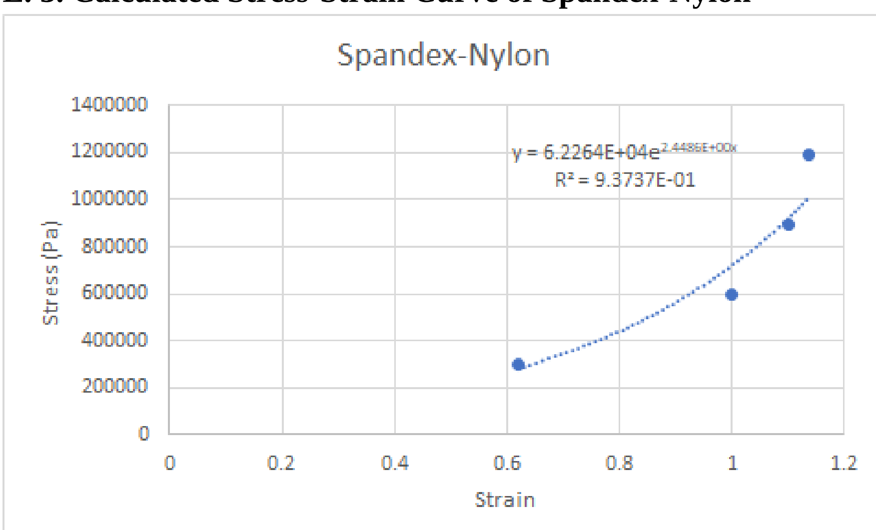
Appendix E. Initial Tensile Testing Data

E. 1. Image of at-home tensile testing set up

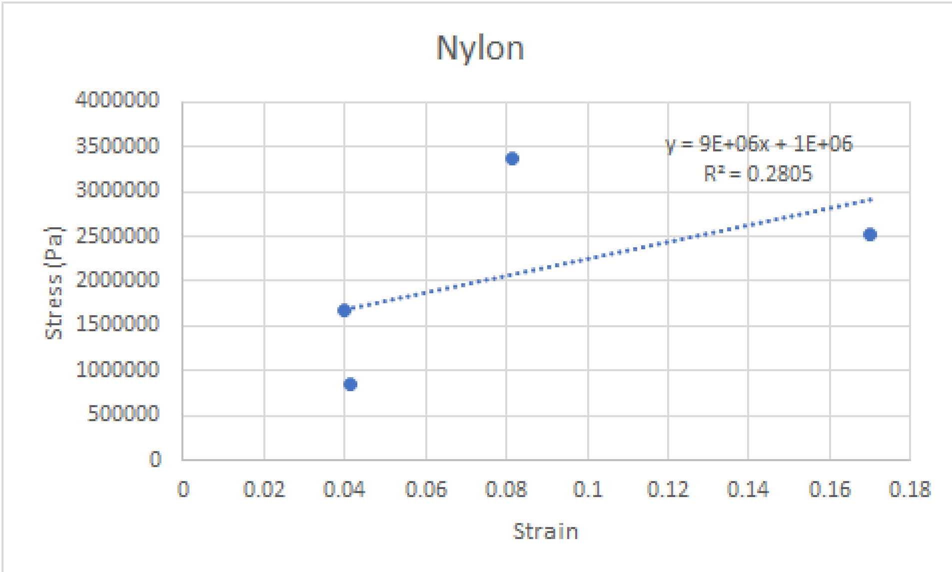
E. 2. Calculated Stress-Strain Curve of Rubber



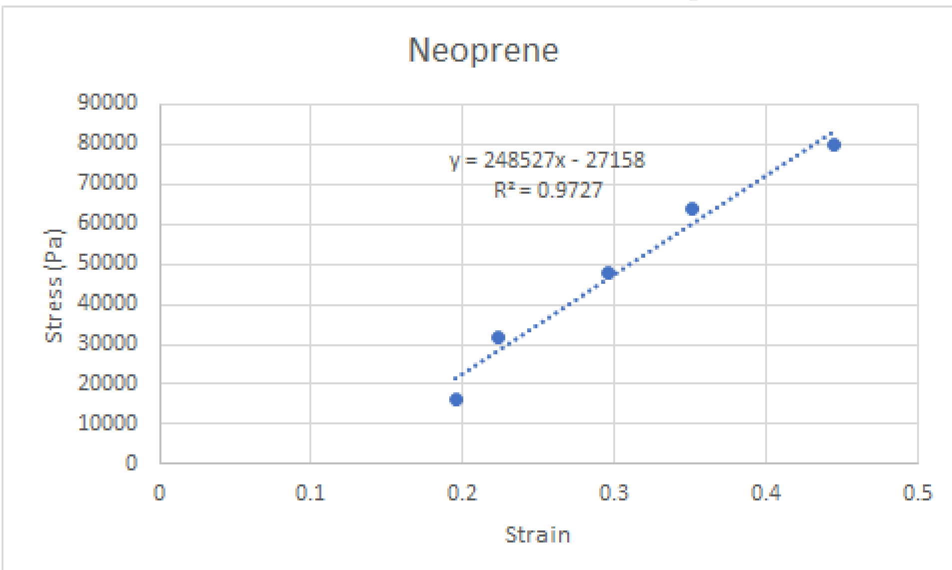
E. 3. Calculated Stress-Strain Curve of Spandex-Nylon



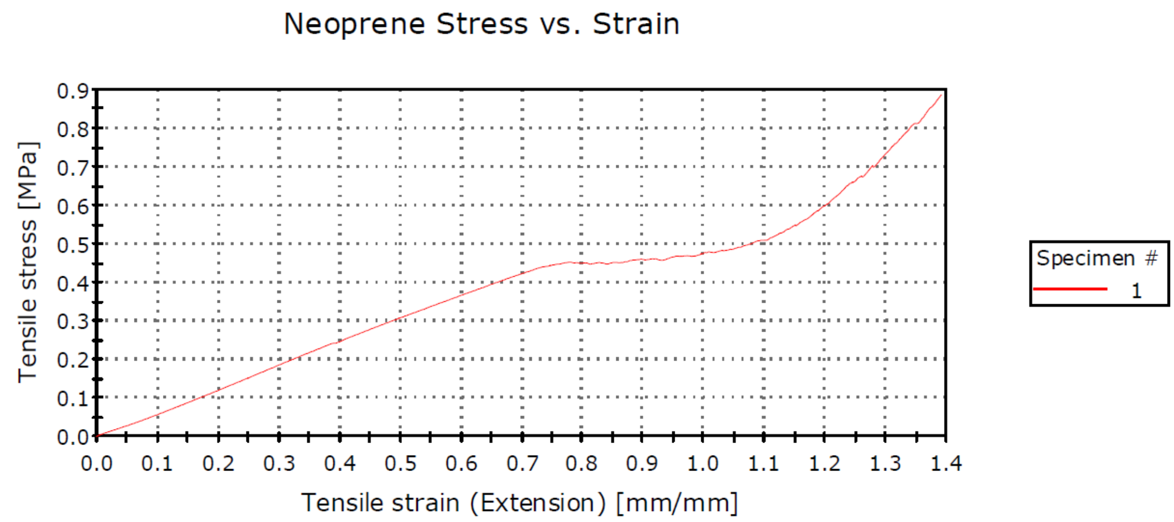
E. 4. Calculated Stress-Strain Curve of Nylon



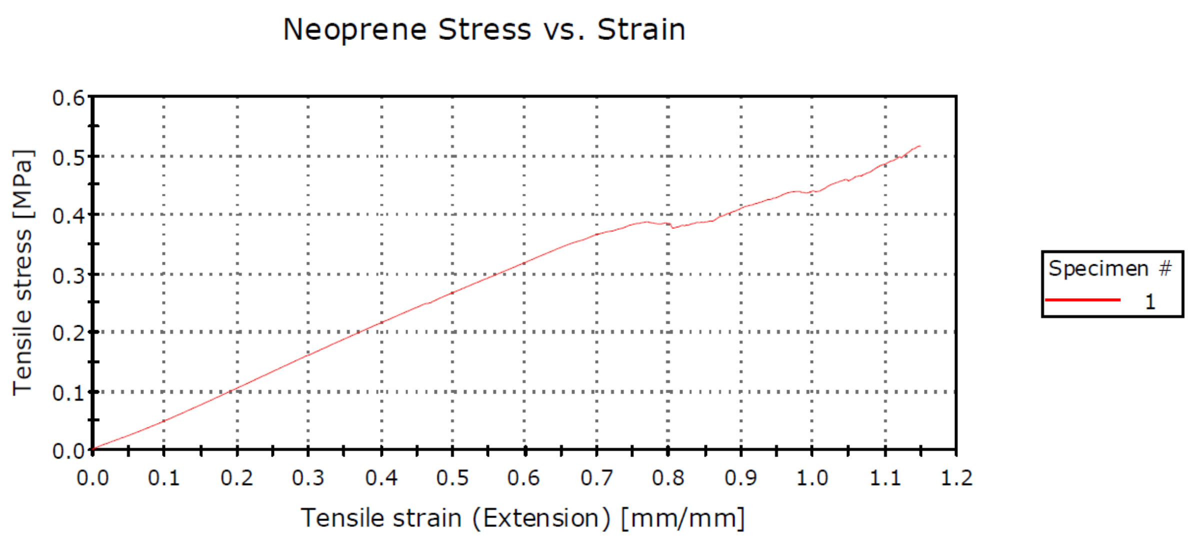
E. 5. Calculated Stress-Strain Curve of Neoprene



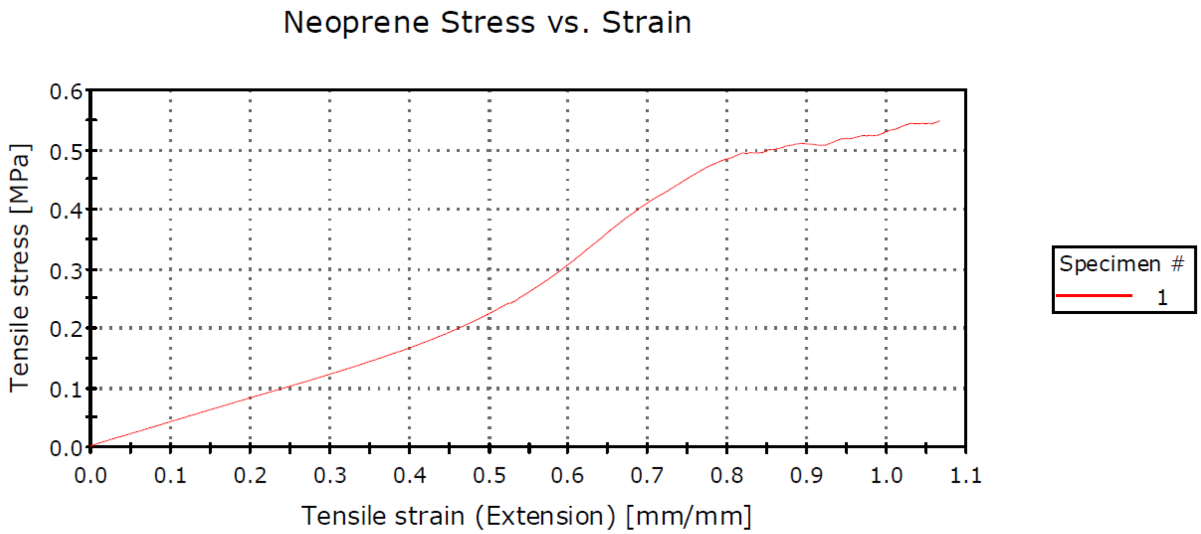
E. 6. Tensile Testing Stress Strain Curve of Neoprene Sample 1



E. 7. Tensile Testing Stress Strain Curve of Neoprene Sample 2



E. 8. Tensile Testing Stress Strain Curve of Neoprene Sample 3



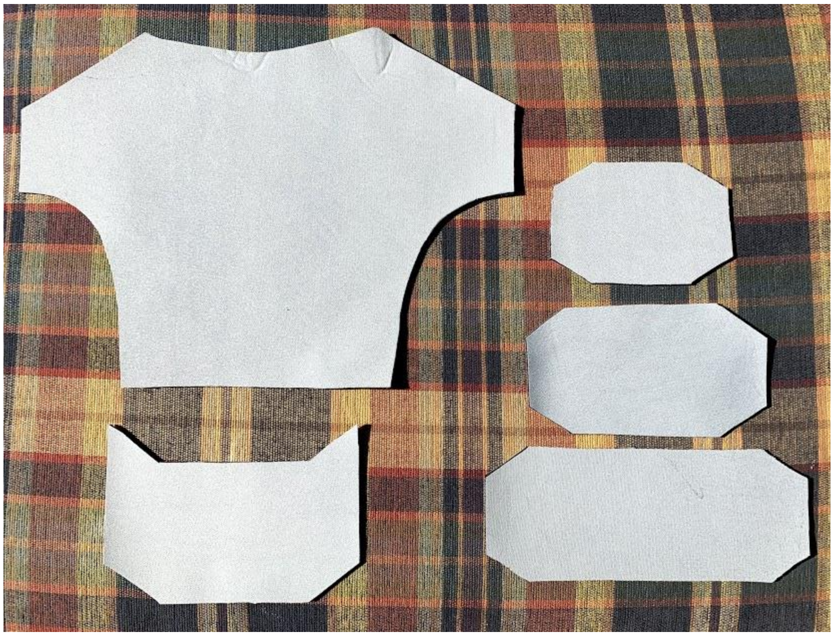
Appendix F. Manufacturing Process Instructions

Manufacturing Process Instructions

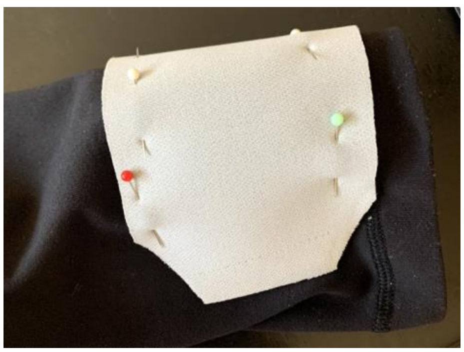
Note: Item numbers correspond to the Bill of Materials (Table 7).

<u>Garment Construction:</u>

1. Using fabric scissors, cut out all panels and patches (see pattern diagram geometry) from the neoprene fabric (Item #3)
   a. Create a pattern using tissue paper. The template should be the same shape and dimensions as described in the detailed geometry.
   b. Pin the tissue paper to the bulk resistant material
   c. Using fabric scissors, cut around the edges of the template to obtain properly sized patches and panel.
   d. Cut one back panel and two of each patch

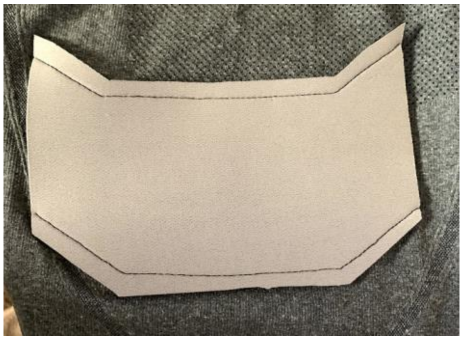


2. Pin the panels onto the base shirt and pant (Item # 1 and 2) in the areas designated by the assembly design



3. Thread the sewing machine with polyester thread and a ball point needle (Item # 4 and 5)
    a. See sewing machine instruction manual for further description of how to thread machine
4. Set the pattern selection dial of the sewing machine to 6, the largest straight stitch

5. Sew the patches of neoprene onto the base garments along the top and bottom edges, leaving the side seams open so that you can thread a resistance band through the patch



6. For the panel, sew around the entire perimeter of the neoprene, attaching it on all edges to the base garment.

7. Once entire length of seam is completed, cut garment from sewing machine

8. Tie off the two threads at the beginning and end of each seam. Trim any remaining thread.

Buckle-Resistance Band Construction:

1. Using fabric scissors, cut the prefabricated cloth resistance band loop (Item #6) so that it is no longer a loop and rather a long resistance strand. Using a lighter, carefully melt the free ends to prevent fraying of the band.

2. Feed one end of the band through the opening on the back of the female buckle attachment (Item #7). Loop the resistance band back through the opening to create a loop.
3. To secure this end of the band in place, feed a wooden dowel (Item #8) through the loop and pull the band tight. This creates the permanent end of the buckle attachment

4. Feed the other end of the resistance band though the opening on the back of the male buckle attachment. The male end has a mechanism that allows for the tightening and locking of the resistance band once it is fed through. This end will allow for user adjustment.

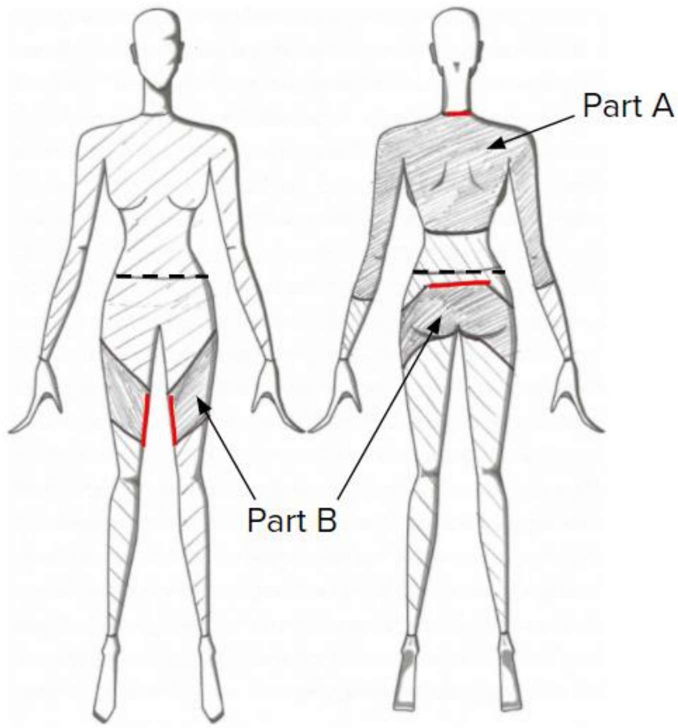
5. Clip the buckle ends together to obtain a fully adjustable looped resistance band. This band will be fed through the patches on the resistance garments.

Appendix G. Itemized Task Descriptions

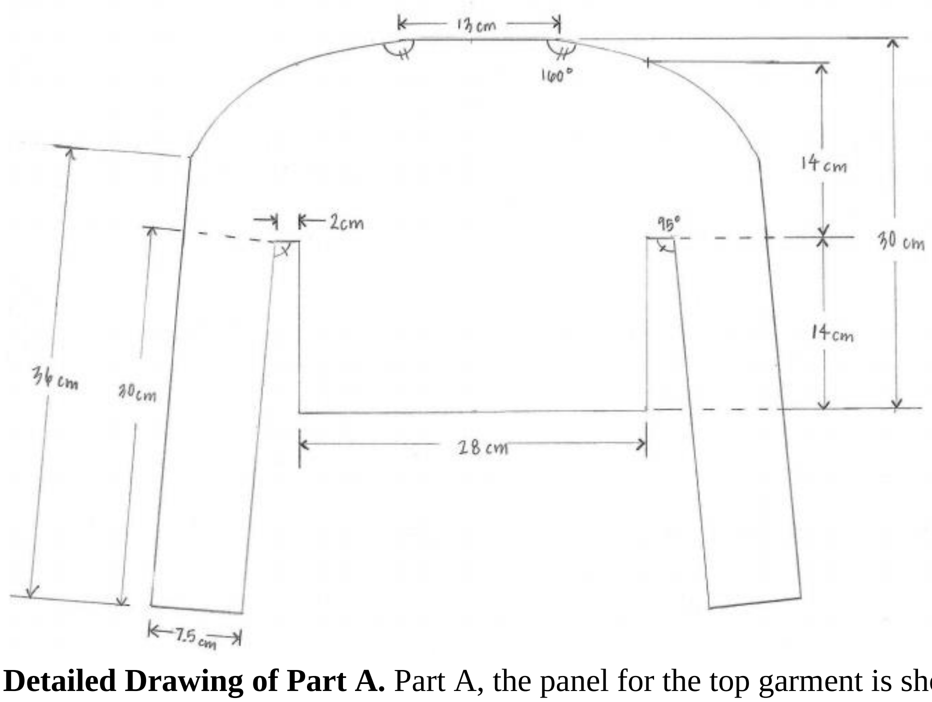
Task #	Task Description	Duration	Start Date	End Date
1	Statement of Work Development	4 days	Mon 9/28/20	Thu 10/1/20
2	Stage 1 Material Research	9 days	Mon 9/21/20	Thu 10/1/20
3	Survey & Survey Analysis	4 days	Mon 9/28/20	Thu 10/1/20
4	Presentation Development	1 day	Fri 10/2/20	Fri 10/2/20
5	Project Planning Meeting	0 days	Mon 10/5/20	Mon 10/5/20
6	Stage 2 Material Research	9 days	Mon 10/5/20	Thu 10/15/20
7	Concept Sketches	4 days	Mon 10/5/20	Thu 10/8/20
8	Pugh Chart	2 days	Fri 10/9/20	Mon 10/12/20
9	FMEA Assignment	4 days	Tue 10/13/20	Fri 10/16/20
10	Conceptual Model Sketches	2 days	Mon 10/19/20	Tue 10/20/20
11	Conceptual Model Governing Equations	1 day	Mon 10/19/20	Mon 10/19/20
12	Conceptual Model Write Up	1 day	Wed 10/21/20	Wed 10/21/20
13	Presentation Development	3 days	Thu 10/22/20	Mon 10/26/20
14	Status Update Memo #1	0 days	Fri 10/16/20	Fri 10/16/20
15	Conceptual Design Review	0 days	Mon 10/26/20	Mon 10/26/20
16	Stage 3 Material Research w/ Risk Assesment	10 days	Tue 10/27/20	Mon 11/9/20
17	Drawing of Tights w/ Detail	4 days	Tue 11/10/20	Fri 11/13/20
18	Status Update Memo #2	0 days	Mon 11/2/20	Mon 11/2/20
19	Status Update Memo #3	0 days	Mon 11/9/20	Mon 11/9/20
20	Presentation Development	2 days	Mon 11/16/20	Tue 11/17/20
21	Critical Design Review	0 days	Wed 11/18/20	Wed 11/18/20
22	Updated Project Plan	3 days	Wed 11/18/20	Fri 11/20/20
23	Material Acquisition	3 days	Mon 1/4/21	Wed 1/6/21
24	Status Update Memo #1	0 days	Thu 1/7/21	Thu 1/7/21
25	Material Testing (For Resistant Material)	3 days	Thu 1/7/21	Mon 1/11/21
26	Sponsor Meeting	0 days	Sun 1/10/21	Sun 1/10/21
27	Prototype Construction	4 days	Sat 1/16/21	Wed 1/20/21
28	Status Memo Update #2	0 days	Tue 1/19/21	Tue 1/19/21
29	Prototype Testing	3 days	Mon 1/18/21	Wed 1/20/21
30	Develop Test Plans	3 days	Mon 1/18/21	Wed 1/20/21
31	Functional Prototype Presentation Development	3 days	Thu 1/21/21	Mon 1/25/21
32	Prototype Video	3 days	Thu 1/21/21	Mon 1/25/21
33	Peer Evaluation & Team Health Assesment	0 days	Wed 2/3/21	Wed 2/3/21
34	Ethics Reflection	0 days	Wed 2/3/21	Wed 2/3/21
35	Prototype Iteration	8 days	Tue 1/26/21	Thu 2/4/21
36	Status Memo Update #3	0 days	Mon 2/8/21	Mon 2/8/21
37	Thermal Conduction Testing	0 days	Fri 2/5/21	Fri 2/5/21
38	Pressure Testing	2 days	Wed 3/3/21	Thu 3/4/21
39	Status Memo Update #4	0 days	Wed 2/17/21	Wed 2/17/21
40	Prototype Function Testing	11 days	Sun 2/21/21	Fri 3/5/21
41	Status Memo Update #5	0 days	Mon 2/22/21	Mon 2/22/21
42	Survey & Survey Analysis on Aesthetics	1 day	Sat 3/6/21	Sat 3/6/21
43	Status Memo Update #6	0 days	Mon 3/1/21	Mon 3/1/21
44	Design Presentation Development	3 days	Sat 3/6/21	Tue 3/9/21
45	Develop Final Report	0 days	Mon 3/8/21	Mon 3/8/21
46	Upload Report to Digital Commons	0 days	Mon 3/8/21	Mon 3/8/21

G.1. Itemized Task List. This figure shows the tasks as shown on the network diagram. All tasks were completed within the dates scheduled in the task list.

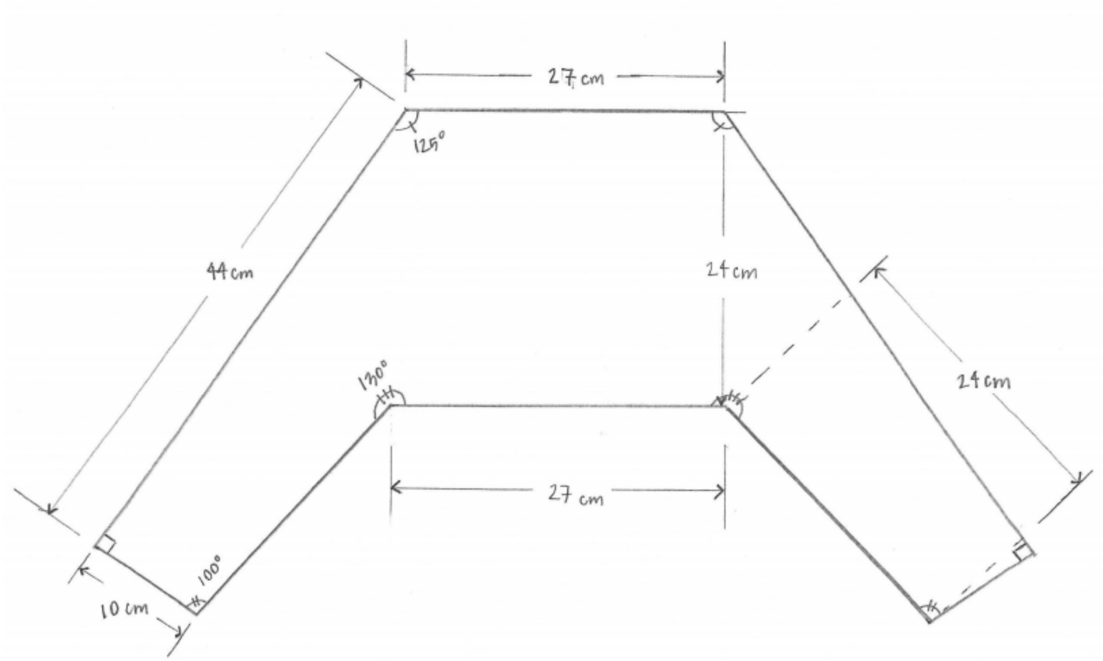
Appendix H. Detailed Design Iterations



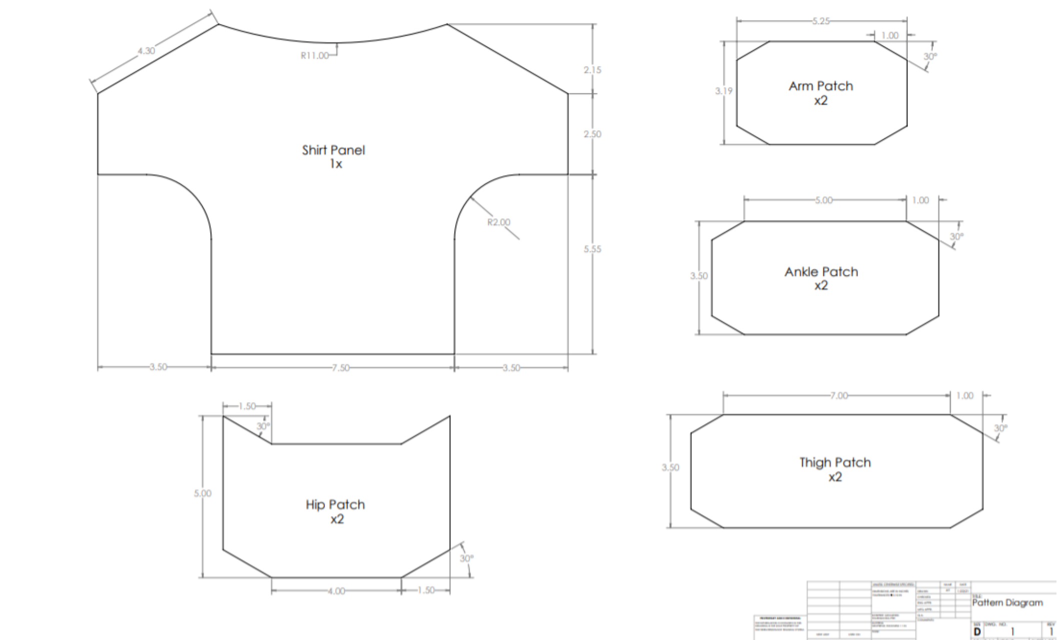
H.1. Detailed Design Assembly. Assembly sketch denotes where paneling will attach to base fabric. Red lines indicate locations at which the paneling will be attached to pre-existing seams on base material. The darker regions in the sketch are the resistant material panels.



H.2. Detailed Drawing of Part A. Part A, the panel for the top garment is shown with actual dimensions for the prototype.



H.3. Detailed Drawing of Part B. Part B, the panel for the bottom garment is shown with actual dimensions for the prototype.



H.4. Original Panel and Patch Dimensions. The only changes made were to the panel, which now extends further out around the shoulders.

Appendix I. User Survey Questions

Questions Asked in User Survey:

1. How would you rank the overall stylistic appeal of the garments on a scale of 1-5?
2. How would you rank the breathability of the garments on a scale of 1-5?
3. How would you rank the overall tightness of the garments on a scale of 1-5?
4. How would you rank the tightness of the LEAST COMFORTABLE part of the garment on a scale of 1-5?

I.1. Participant Responses

Timestamp	Question 1	Question 2	Question 3	Question 4
2/26/2021 18:19:03	4	5	2	1
2/26/2021 18:50:11	4	4	4	3
2/28/2021 13:21:29	4	5	5	3
2/28/2021 17:58:19	3	5	5	3
3/5/2021 15:12:28	4	3	4	2
3/5/2021 15:17:39	3	5	5	5

Appendix J. Specification Testing Raw Data

J.1. Efficacy Data (Control)

	Control - Normal Clothes				
Participant	Resting HR	Walking HR	Push Ups HR	Lunges HR	Lateral Raises HR
1	73	75	84	105	89
2	68	76	111	128	67
3	77	98	80	112	72
4	69	92	72	94	91
5	80	116	121	140	110
6	89	102	123	156	133
7	100	109	128	158	121
St. Dev	11.55937055	15.61897503	23.32176584	25.05897805	24.71070715
SE	4.3690314	5.903417666	8.814798935	9.471403433	9.339769404
avg	79.42857143	95.42857143	102.7142857	127.5714286	97.57142857

J.2. Efficacy Testing Data (Experimental)

	Experimental - Resistance Training System					
Participant	Resting	Walking	Push Ups	Lunges	Lateral Raises	Resistance garment worn 1st or 2nd?
1	73	85	90	124	87	2
2	65	84	118	134	62	1
3	77	74	112	120	64	2
4	84	105	102	121	103	2
5	91	118	137	144	116	1
6	87	120	147	154	123	2
7	98	93	129	154	120	1
St. Dev	11.26	17.76	19.95	14.95	25.86	-
SE	4.256	6.712	7.539	5.650	9.776	-
Avg	82.14	97	119.3	135.9	96.43	-

J.3. Heart Rate Elevation Data (Control)

Control Heart Rate Elevation (BPM)			
walk	pushups	lunges	lateral raises
2	11	32	16
8	43	60	-1
21	3	35	-5
23	3	25	22
36	41	60	30
13	34	67	44
9	28	58	21

J.4. Heart Rate Elevation Data (Experimental)

Experimental Heart Rate Elevation (BPM)			
walk	pushups	lunges	lateral raises
12	17	51	14

19	53	69	-3
-3	35	43	-13
21	18	37	19
27	46	53	25
33	60	67	36
-5	31	56	22

J.5 Statistical T-tests

Paired T-tests				
Test Type	Walking	Push Ups	Lunges	Lateral Raises
Total Heart Rate	0.399900562	0.006100126	0.048391898	0.355790785
Heart Rate Elevation	0.42656829	0.008439443	0.076233222	0.011153213

J.6.i Thermal Insulation Data

Garment Area	Temp Difference ©	Ice mass beginning (g)	Mass left on Sheet (g)	Time (min:s)	Ice Mass End (g)
Leg	65	28.15	0.48	10:23	16.11
Waist	65	29	0.72	10:05	21.04
Ankle	65	19.11	0.42	10:00	14.55
Stomach	65	27.77	0.44	10:12	16.07
Arm	65	17.88	0.29	10:25	9.46

Control	22.7778	27.64	0.58	10:00	22.9

J.6.ii Thermal Insulation Data

Garment Area	Ice Area (in^2)	Heat transfer rate (J/s=W)	Insulation Constant (Clo)
Leg	2.4	3.882	0.1673
Waist	2.4	1.681	0.3862
Ankle	2.4	-0.01113	-58.32
Stomach	2.4	3.829	0.1696
Arm	2.4	2.029	0.3200
Control	2.4	2.316	

J.7 Pressure Data

Body Part	Left Pressure (mV)	Right Pressure (mV)	Conversion Factor g/(cm^2*mV)	Average (g/cm^2)

Hip	2.2	2	0.3125	0.6562
Buttock	1.95	1.85	0.3125	0.5937
Back Calf	1.53	1.43	0.3125	0.4625
Mid Calf	1.41	1.2	0.3125	0.4078
Shoulder Blade	1.5	1.3	0.3125	0.4375
Deltoid	1.1	0.8	0.3125	0.2969
Waist	1	0.82	0.3125	0.2844